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The Information for Catching Fly Balls: Judging and Intercepting Virtual Balls in a CAVE

Frank T. J. M. Zaal and Claire F. Michaels
Vrije Universiteit

Visually guided action implies the existence of information as well as a control law relating that information to movement. For ball catching, the Chapman Strategy—keeping constant the rate of change of the tangent of the elevation angle (d(tan(α))/dt)—leads a catcher to the right location at the right time to intercept a fly ball. Previous studies showed the ability to detect the information and the consistency of running patterns with the use of the strategy. However, only direct manipulation of information can show its use. Participants were asked to intercept virtual balls in a Cave Automated Virtual Environment (CAVE) or to judge whether balls would pass behind or in front of them. Catchers in the CAVE successfully intercepted virtual balls with their forehead. Furthermore, the timing of judgments was related to the patterns of changing d(tan(α))/dt. The advantages and disadvantages of a CAVE as a tool for studying interceptive action are discussed.

The visual guidance of goal-directed movement implies the existence of information for controlling that movement as well as a control law expressing the relation between this information and the forces to be exerted by the organism to realize that movement. It is the task of the student of perception-action to discover both the implied information and the control laws for the task under study. For the specific task of catching a fly ball, some progress has been made in identifying the information as well as the control law associated with this information. In this article we argue, however, that not all alternatives have been ruled out by previous studies. To provide an unequivocal test of whether the rate of change of the tangent of the elevation angle (or, equivalently, optical acceleration; definitions are given below) is the information used in fly-ball catching, we performed experiments using virtual reality techniques while at the same time assessing the usefulness of virtual reality for the study of perception-action tasks such as catching fly balls.

Most of the theoretical work on the interception of fly balls bears at least some relation to the proposal made by the physicist Seville Chapman in 1968. He considered the situation in which a ball travels along the sagittal plane toward a fielder. Chapman ignored the effects of air resistance (drag) on the ball and consequently assumed that the ball would follow a parabolic path. His mathematical analysis showed that the tangent of the angle of elevation, defined as the angle α between the horizontal and the line connecting the ball with the point of observation, increases at a constant rate if the ball will land exactly at the point of observation. A constant optical velocity, that is, a constant d(tan(α))/dt, will also occur if a catcher runs at a constant speed to arrive at the landing location of the ball at the same time as the ball does. An increasing d(tan(α))/dt specifies that the ball will fly over the catcher's head. To catch the ball, the catcher should start running backward or, if he or she is already running, increase speed in the backward direction. The opposite is true if d(tan(α))/dt is decreasing. This specifies that the ball is going to land in front of the catcher and that he or she should start running forward or, if already running, increase speed in the forward direction. Figure 1 illustrates Chapman's analysis. The upper row of panels shows a ball following a parabolic path (solid line) over a distance of 30 m, reaching a height of 5 m. In Figure 1B, the ball arrives exactly at the point of observation, at point (0, 0). We plotted the ball at equal intervals throughout its flight. Because the distances of the line segments between the crossings of the dashed lines and the *y*-axis are evenly spaced, the tangent of elevation angle α increases at a constant rate. Figures 1A and 1C present the same ball path, but now the points of observation have been moved to (−2.5, 0) and (+2.5, 0), respectively, so that the ball lands behind the point of observation in Figure 1A and in front of the point of observation in Figure 1C. The former situation gives rise to an increasing d(tan(α))/dt, and the latter situation results in a decreasing d(tan(α))/dt.

Chapman's analysis suggests a simple strategy for running to catch a fly ball: Run in such a way that the rate of change of the tangent of the angle of elevation stays constant, and one will arrive at the right location. It is important to note that this strategy works without a need to know in advance where or when the ball will

Frank T. J. M. Zaal and Claire F. Michaels, Institute for Fundamental and Clinical Human Movement Sciences, Vrije Universiteit, Amsterdam, the Netherlands.

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Correspondence concerning this article should be addressed to Frank T. J. M. Zaal, who is now at the Institute of Human Movement Sciences, University of Groningen, P.O. Box 196, NL-9700 AD Groningen, the Netherlands. E-mail: f.zaal@ppsw.rug.nl

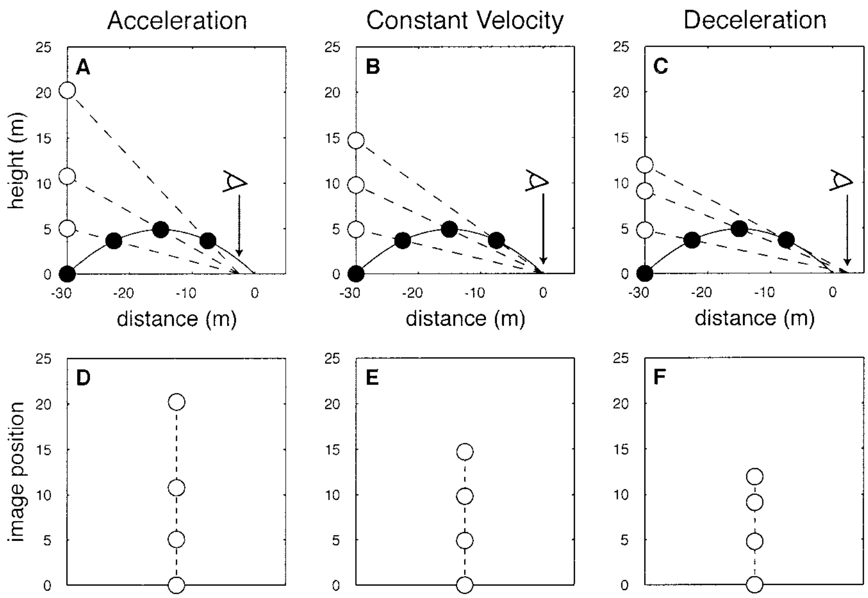

Figure 1. An illustration of Chapman's (1968) optical analysis. Panels A–C depict balls that approach a point of observation via a parabolic path (solid lines). The point of observation is at (−2.5, 0) in Panel A, at (0, 0) in Panel B, and at (+2.5, 0) in Panel C. Dashed lines indicate the line of sight at equal time intervals. Panels D–F show the optical position of the ball at the same points in time. The projection plane was taken at the position of the *y*-axis in Panels A–C.

land. A number of studies concluded that the running patterns of fly-ball catchers were consistent with the Chapman Strategy (McLeod & Dienes, 1993, 1996; McLeod, Reed, & Dienes, 2001; Michaels & Oudejans, 1992). We discuss these studies and their conclusions later, but first we address concerns that have been raised regarding the Chapman Strategy. The main concerns have been (a) the (in)capacity of the human visual system to detect optical acceleration, (b) the consequences of the assumption of parabolic ball trajectories, and (c) the fact that catchers do not run at constant speeds.[1]

The Detection of Optical Acceleration

The use of the Chapman Strategy implies the human ability to detect the nonuniformity of $d(\tan(\alpha))/dt$. Strictly speaking, and despite the reading given in Tresilian (1995), the strategy does not require the rate of acceleration of the catcher to be proportional to the rate of acceleration of the tangent of the angle of elevation. The use of the strategy requires the catcher to be able to detect that $d(\tan(\alpha))/dt$ is increasing or decreasing and to accelerate in the appropriate direction until the rate of change has become constant again.

The ability to detect the nonuniformity of $d(\tan(\alpha))/dt$ has been studied by asking people to judge the uniformity of the speed of moving computer images. Mathematically, $d(\tan(\alpha))/dt$ and the speed of the projection of the ball onto a vertical image plane are equivalent, as is clear from Figure 1. Thus, the Chapman Strategy can just as well be framed in terms of canceling out optical acceleration on the image plane, that is, zeroing image acceleration[2] (e.g., Babler & Dannemiller, 1993; McBeath, Shaffer, & Kaiser, 1995; Michaels & Oudejans, 1992). Several studies have claimed, however, that human observers have difficulty detecting optical acceleration (e.g., Calderone & Kaiser, 1989; Schmerler, 1976). This would be a serious problem for a model that explains the control of catching balls on the basis of optical acceleration. The answer to this apparent problem is twofold. First, the Chapman Strategy asks only for the detection of the nonuniformity of optical velocity, that is, for the detection of the occurrence of acceleration rather than for the amount of acceleration. It is the amount of acceleration that human observers cannot report very well; they are able to distinguish acceleration from nonacceleration if the acceleration is above some threshold value (Babler & Dannemiller, 1993; Brouwer, Brenner, & Smeets, 2002; Michaels & Oudejans, 1992). Moreover, participants who were asked to watch moving dots on a computer screen, with an instruction to see the moving dot as a simulated ball approaching along the sagittal

[1] A point of critique that we do not discuss at length here is that the Chapman Strategy would only apply to balls flying in the midsagittal plane, thus restricting the applicability of the strategy to a rather limited set of natural circumstances. However, the recent study by McLeod et al. (2001) clearly showed that also in cases where catchers' running patterns have significant lateral components, $d(\tan(\alpha))/dt$ remains essentially constant while running to catch the ball.

[2] In defining optical variables, one can use an image plane or optical angles. For small angles, the choice is immaterial; for larger angles, the two are different. To distinguish the variables, we refer to *image variables* (e.g., image velocity and image acceleration) and to *angular variables* (e.g., angular velocity and angular acceleration). In some cases, we simply refer to *optical acceleration* or *optical velocity* to express that we consider the variables in a more general sense without reference to their specific definition.

plane, could accurately judge whether these simulated balls passed in front of, behind, or at their position (Babler & Dannemiller, 1993; Michaels & Oudejans, 1992).

Assuming that the nonuniformity of image velocity can be detected, one still can ask what exactly it is that the perceptual system detects. One option is to detect a quantity that physics defines as acceleration, that is, to detect the time derivative of image velocity. But detecting any change in velocity would serve the same purposes. The latter perspective has been adopted in more recent studies on the perception of acceleration (i.e., the nonuniformity of image velocity). However, no principled choice or sound empirical basis for the variable representing acceleration has been provided by these studies. For instance, Schmerler (1976) employed the ratio of the terminal velocity and the initial velocity of his stimuli to study the perception of acceleration. He called this variable the *velocity ratio*. Later, Calderone and Kaiser (1989) used the same term to denote the difference of terminal velocity and initial velocity, divided by the average velocity of their stimuli. The latter definition was also adopted by Babler and Dannemiller (1993) in their work on the perception of the future landing location of approaching objects. But Babler and Dannemiller went a step further. They compared their observers' judgments both with acceleration according to its physics definition and with the velocity ratio. This comparison strongly suggested that the velocity ratio was the better characterization of detected acceleration (cf. Brouwer et al., 2002). Still, some questions remain. Babler and Dannemiller had to make an assumption about the time interval over which the velocity ratio was to be defined, for which they chose the entire stimulus event. Obviously, other choices are possible. Moreover, in natural situations, there are event durations but not stimulus durations, and the duration of the interval defining the velocity ratio ought to be chosen on principled grounds. How long is optical velocity sampled to detect any differences therein? And, if relating the use of a velocity ratio to some action measure (say, an initiation to run forward or backward), what is the delay between picking up the information and the experimentally detectable action?

A final point concerning the detection of acceleration concerns perceptual systems. As laid out in Oudejans, Michaels, Bakker, and Davids (1999), at one extreme, catchers could track the ball with their eyes (and head) such that the image of the ball would not move across the retina. Extraretinal signals, such as signals from the vestibular system and from neck-muscle or eye-muscle proprioception, might then be involved in the detection of the change of eye orientation (the tilt angle with respect to the horizon being most relevant here). If this were the case, optical information would be detected mainly by extraretinal systems (of course, retinal signals play a role in the tracking of the ball). Alternatively, retinal signals could be involved in the pick up of optical acceleration even if the image of the ball on the retina were not moving. This would be possible because in tracking the ball, the projection of the visual background structure would move across the retina. Potentially, the rate of change of the velocity of this background movement could inform the catcher about the appropriate action (cf. Oudejans et al., 1999). Finally, the other extreme case would be the situation in which the eyes and head do not move (tilt) during the act, such that acceleration of the ball's image would constitute the information for the catcher. This situation would occur, for instance, if observers fixated a stationary point. Interestingly, this resembles the task in many studies of the perception of optical acceleration. Observers typically watch events displayed on rather small computer screens (e.g., Babler & Dannemiller, 1993; Brouwer et al., 2002; Calderone & Kaiser, 1989, Michaels & Oudejans, 1992; Todd, 1981), thereby restricting eye and head movement.

The Effects of Air Resistance

A ball traveling through the earth's atmosphere is subject to air resistance, the amount of which is roughly proportional to the squared velocity of the ball. As a result, the ball will not follow a parabolic trajectory. Although Chapman (1968) assumed that this deviation from a parabolic trajectory is so small that it can be readily ignored, a closer examination of the physics of fly balls shows that this is not the case. Air drag can cause a reduction in the traveled distance of about 50% (Adair, 1994; Brancazio, 1985). The consequence is that the tangent of the angle of elevation does not change at a constant rate for a ball destined to land at the point of observation. Therefore, Brancazio argued, Chapman's strategy cannot work.

Although Brancazio's (1985) claim might be true for the stationary observer, Chapman's strategy can certainly be functional in the more natural situation of a moving catcher. As shown by elaborate analyses (Dienes & McLeod, 1993; McLeod & Dienes, 1996; Tresilian, 1995), if a catcher runs so as to keep the rate of change of $\tan(\alpha)$ constant, this catcher will arrive at the right place at the right time even when there is drag. The Chapman Strategy is self-correcting (Michaels & Zaal, 2002; Tresilian, 1995). In running in a way that adheres to the Chapman Strategy, however, the catcher violates another assumption in Chapman's original formulation of the model, which was that catchers run at constant speeds. Although this assumption was unrealistic to start with, the fact that catchers run at nonuniform speeds was also demonstrated by McLeod and Dienes (1993, 1996), who videotaped the running patterns of cricket players. Running so as to keep $d(\tan(\alpha))/dt$ constant while balls fly through the earth's atmosphere necessarily leads to running speeds that are not constant.

In sum, we take the current version of the Chapman Strategy to be a self-correcting strategy that does not rely on a parabolic ball trajectory or on the uniformity of the running speed profiles. When we refer to the Chapman Strategy, it is this version that we have in mind.

Do Catchers Adhere to the Chapman Strategy?

To answer the question of whether catchers adhere to the Chapman Strategy, one should study catching itself.[3] Michaels and Oudejans (1992) were the first to present such data. Catchers were videotaped, and their running patterns were determined from the digitized video images. Michaels and Oudejans showed that their participants indeed ran in a way that tended to keep optical speed constant throughout the run (optical speed deviated from con-

[3] Although studies asking observers to judge the future passing side (in front or behind) of (simulated) balls might provide evidence that observers make these judgments on the basis of optical acceleration (e.g., Babler & Dannemiller, 1993; Michaels & Oudejans, 1992), the use of optical acceleration in such a task cannot be generalized to the adherence to a Chapman Strategy, which claims a continuous control of locomotion on the basis of that variable. Later in this article we present further evidence that one needs to study the situation with locomotion to make claims on the use of the variables implied in the control of locomotion.

stancy close to the point of interception). At about the same time, McLeod and Dienes (1993, 1996) presented results from a study in which cricket players had to catch cricket balls that were projected at them from a bowling machine. As mentioned previously, running speed turned out not to be constant. Furthermore, McLeod and Dienes (1996) also showed that catchers are still running at the moment of interception, thus supporting the tenet that the control of running to catch is on the basis of continuous guidance and not on the basis of estimating a landing location and time. In the latter case, catchers are expected to be waiting for the ball to arrive at the landing site. In addition, they would also be expected to run to the same location in the same way, irrespective of how the ball gets there. This is not the way catchers run. McLeod and Dienes (1996) showed that running patterns in their study did vary depending on the details of the ball trajectory.

The fact that catchers run in a way consistent with the Chapman Strategy does not mean that they necessarily use that strategy; it may be that other strategies and other information result in the same running patterns. Conclusive evidence for the use of some information can be obtained only from directly manipulating that information in a conscientious attempt to disprove its use. To do so, one needs to be able to play with ball trajectories and their optical consequences and study the reactions to the perturbations. The actual-catching studies discussed previously could not have adopted this method because nature is rather stubborn in allowing controlled perturbations to ball trajectories, and even more so in permitting any uncoupling of ball flight details from optical consequences. Therein lies the rationale for the present studies, in which we used virtual reality techniques to study ball catching. Obviously, manipulating ball trajectories as well as playing with the optics is done easily in virtual reality, a feature that might make this technology a valuable tool in the study of interceptive tasks.

Catching Virtual Balls in a CAVE

For our study we used a Cave Automated Virtual Environment (CAVE) situated at Academic Computing Services Amsterdam (SARA) in Amsterdam. This CAVE is an approximately 3- × 3- × 3-m space that surrounds a freely moving viewer with computer display screens. Computer-generated images are projected on three walls and the floor of the CAVE (Cruz-Neira, Sandin, DeFranti, Kenyon, & Hart, 1992). The motion of the viewer is tracked such that the computer images can be updated to the viewer's perspective at a high frame rate. As mentioned previously, the CAVE allows the study of interception under unnatural conditions. Ball trajectories can be parabolic or nonparabolic, shaped to specific designs, and even changed on the fly as a function of the movement of the participant. Furthermore, one can play with the coupling of ball movement and its optical consequences. For instance, balls can be simulated to have a natural optical speed but unnatural optical expansion. A strict version of the Chapman Strategy would predict that this manipulation would not affect the catching behavior. However, before we allow ourselves to leap into experiments such as these, let us consider some potential disadvantages of doing research in the CAVE.

Catching virtual balls in the CAVE is different from catching real balls out in the field. For example, in the CAVE there is limited room in which to walk, and catchers in the CAVE wear equipment such as shutter goggles, which restrict the field of view, and a sensor for movement registration, which connects to the tracking device through a wire. This wire might get into view and might also interfere with free movement. Another physical limitation of the CAVE that we used is the lack of projection screens above and behind the observer, which prevents complete immersion. Furthermore, in the CAVE the virtual world has to be created completely through vision (and, possibly, acoustics). At the time of the experiments, SARA's CAVE setup did not include a data glove, which would have made it possible to provide tactile feedback to participants. Finally, the virtual world operates at discrete temporal and spatial resolution, with different frames of reference for the movement tracking system and the projection system, as well as time lags between movement registration and the updating of the optics. With these possible limitations in mind, our first goal was to see whether people could actually intercept virtual balls in the CAVE, and if so, how these interceptions relate to catches in the world outside the CAVE.

The merits of a virtual environment such as the CAVE for the study of perception-action can be assessed in different ways. At one extreme, one can opt for a direct within-subject comparison of performance in a virtual environment with that in a similar real-world task. The other extreme would be to perform between-subjects and between-experiments comparisons of the performance in the virtual-world task with the performance in similar tasks reported in the literature. Bingham and colleagues, for instance, in their recent study of visually guided reaching, chose the first route (Bingham, Bradley, Bailey, & Vinner, 2001). They had people reach to multiple positions near the surface of spherical targets, which were either real or simulated in (head-mounted) virtual reality. The task was carefully modeled on a previous experiment (Bingham, Zaal, Robin, & Shull, 2000) so that the experiments in the real-world task took the form of a replication. The first experiment in the Bingham et al. (2001) study had participants perform the reaches while vision of both the hand and the target was allowed throughout the reach. It is important to note that reaches to the back of the target surface were different in the real and virtual worlds. Reaches in the virtual-world task that were to be aimed at about a centimeter behind the farthest target surface ended up roughly in the center of the target, whereas the corresponding reaches in the real-world task came out roughly accurate. In spite of the differences, Bingham et al. (2001) did not conclude that the virtual-reality setup was inappropriate to study real-world behavior; instead, they argued that people use disparity matching in their control of reaching, which explained why the reaches in the virtual-reality task ended up at about the center of the virtual target sphere. As to the reaches in the real-world task, solid spheres do not allow reaches to end up in their centers; these reaches therefore end up roughly accurate. This example illustrates the dilemma encountered by the researcher using virtual reality. Differences are bound to be found, and finding differences is actually part of the goal in using virtual-reality techniques. At the same time, one has to be convinced that the findings from virtual-reality experiments can be generalized to reality. Our choice in setting the stage for generalizability was to make the virtual situation comparable to previous experiments.

Experiment 1

To establish that catching and judging virtual balls resembles catching and judging real balls under similar conditions, we designed our first CAVE experiment along the lines of the Oudejans et al. (1999) study, in which participants had to run in a completely dark gym to catch luminous balls. One advantage of using this situation in the CAVE experiments was that no decisions had to be made about how to represent the environment graphically. The drawn images were essentially white expanding circles, representing approaching balls, rising on a black background. Furthermore, the computations for this display were minimal, yielding optimal time lags. We had participants perform two tasks. In a judgment condition, participants were to judge whether an approaching ball would pass behind or in front of them. In a catching condition, participants had to intercept the virtual ball with one hand or, more precisely, with a hand-held pointing-and-tracking device (see the *Apparatus* section). The judgment condition was modeled on studies of the ability to see acceleration (e.g., Babler & Dannemiller, 1993; Brouwer et al., 2002; Michaels & Oudejans, 1992; Todd, 1981), and the catching condition was modeled on studies of real catching (e.g., McLeod & Dienes, 1996; McLeod et al., 2001; Michaels & Oudejans, 1992). In addition, because judging and catching are studied under the same conditions, this setup would also allow a comparison of these two paradigms, both of which have been used to address the natural interception of approaching balls.

Method

Participants. Five men and 5 women, 22 to 33 years of age, volunteered to participate in the experiment.

Apparatus. We performed our experiments in the CAVE that is situated at SARA (Academic Computing Services Amsterdam). The CAVE has three 10-ft × 10-ft (3.05-m × 3.05-m) rear-projection screens that are walls of a cube-shaped space. Computer images, at a resolution of 1,280 × 1,024 pixels, are projected onto these three walls and onto the floor at a frequency of 120 Hz (projection frame rate) through video projectors and mirrors. The computer images are generated on a Silicon Graphics Industries Onyx2 RealityMonster system with 8 MIPS R10000 processors running at 200 MHz and 1 GB of RAM. The RealityMonster at SARA was the first of its kind to be installed. A stereoscopic effect is obtained by alternately projecting the computer images for the left and the right eyes. Viewers wore Stereographics CrystalEyes liquid crystal (LC) shutter glasses (Stereographics Corporation, San Rafael, CA) that allow viewing with the right and left eye in synchrony with the computer images for those eyes. A Flock-of-Birds system (Ascension Technologies Corporation, Burlington, VT) is used to track the movement of the viewer. Tracking occurred at approximately 40 Hz (motion tracking rate). One Flock-of-Birds sensor is attached to the shutter glasses. Tracking of this sensor makes it possible to refresh the computer images to the perspective of the viewer. Another sensor is attached to the "wand," a hand-held input device with three buttons and a joystick. Participants used the buttons on the wand to report their judgments. All CAVE processes were monitored at a frequency of about 100 Hz (sampling rate). This means that the kinematic data records we obtained were samplings (at 100 Hz) of the position data records of the Flock-of-Birds sensors, which tracked movement at about 40 Hz. Successive entries in the kinematic data records could thus be identical.

We ran several tests to check the specifications of the CAVE. One such test was designed to reveal the time lag between head movements and the updating of the computer images based on that movement. We performed this test after completing Experiment 3. We had the shutter glasses and, thus, the attached sensor make a swinging movement, and we projected an object on the front wall of the CAVE. We videotaped both the swinging shutter glasses and the moving projection of the object. A cross-correlation of the digitized position data of the shutter glasses and of the projected object had a peak at a lag of 5 (50 Hz) video frames. We concluded from this that the delay between sensor movement and updating of the images was between 80 and 120 ms.[4]

Procedure and design. In the judgment condition, a trial started with the projection of a white circle on the center of the floor, indicating the place for the participant to stand. Next, the ball was shown at its starting position. After a signal from the participant that he or she was seeing the ball, it started its approach to the participant. The participant was instructed to press one of two buttons on the wand to enter the judgment. The participant held the wand with two hands, keeping the thumbs on the two outer buttons. The instruction to the participant was to push the button as soon as he or she knew where the ball would pass at eye level. We explicitly told the participant that that meant that they should not wait until the trial was finished. For half of the participants, the left button represented balls going to pass in front of the head, and the right button represented balls going to pass behind the head. This was reversed for the other half of the participants. No feedback on performance was given. Balls always started at floor level at a distance of 30 m and reached a highest point of 7.7 m during their parabolic flight of 2.26 s. In one block of trials, balls passed either 5 m in front of the point of observation or 5 m behind the point of observation, assumed to be 1.7 m above the floor. In another block of trials, balls passed at a distance of 1 m in front of or behind the point of observation. The 5-m and 1-m conditions were termed the *far* and *near* conditions, respectively. Projection of the ball stopped when the ball passed below eye level. The ball diameter was 0.20 m. Balls could be viewed either monocularly or binocularly. During monocular viewing, the participant wore a patch over the left eye while the CAVE ran in the stereoscopic mode. Five repetitions of each trial were presented. Combining the two viewing conditions and the two sets of passing distances yielded four blocks of 10 judgment trials.

Trials in the *catching* condition also started with the projection of a white circle in the center of the CAVE floor. Participants were instructed to step onto this circle to take the initial position for receiving the ball. After a ready signal, the ball was shown at its starting position. Participants signaled that they saw the ball, after which the ball started its approach. The instruction to the participant was to intercept the ball with the hand-held wand, letting the ball fly through the wand. As in the judgment condition, 0.20-m balls came from a distance of 30 m and reached a highest point of 7.7 m. Balls followed the same trajectory as in the near judgment conditions. However, because participants were free to move, passing distances with respect to the actual points of observation were a function of the actual head movement. Ideally, including a catching condition in which balls could pass 5 m behind or in front of the initial point of observation would have made the design symmetrical, but the limited space of the CAVE did not allow locomotion more than 1.5 m from the center of the CAVE floor. As in the judgment condition, balls could be viewed either monocularly or binocularly. We delivered five repetitions per trial, leading to two blocks of 10 catching trials.

Trials were blocked by viewing condition, the order of which was balanced across participants. Within each viewing condition, three blocks of 10 trials of the near, far, and catching condition were presented. Each of these three blocks had only two types of trials, that is, trials passing in front of the (initial) point of observation and trials passing behind the (initial) point of observation. The order of blocks within a single viewing condition

[4] Because every CAVE is unique in its setup, performance of the hardware and software will be different from CAVE to CAVE. For instance, the delays at the CAVE at Indiana University are about 160–200 ms (G. P. Bingham, personal communication, 2001).

was randomly chosen, with the proviso that the catching condition could never be the first or last condition in the experiment. Each block of 10 trials was preceded by 2 practice trials, resulting in a total of 72 trials per participant.

Results

Judgment task. Participants were able to judge well whether a ball would land behind or in front of them (see Table 1); with the exception of the balls that were to pass at the near distance in front of the participants, judgment errors were rather few. A repeated measures analysis of variance (ANOVA) on number of correct responses, with factors of viewing (binocular vs. monocular), passing distance (far vs. near), and passing side (in front vs. behind), indicated that at the near passing distance, fewer correct responses were given than at the far passing distance, $F(1, 9) = 14.5$, $p < .01$, and also that fewer correct responses were given to balls passing in front of the observer than to balls passing behind, $F(1, 9) = 8.4$, $p < .01$. The viewing effect just failed to reach significance, $F(1, 9) = 4.7$, $p = .06$. None of the interaction effects was significant.

Table 1 also gives the average response times of the trials in which a correct response was given. An ANOVA analogous to that described above yielded a significant passing distance effect, $F(1, 8) = 90.6$, $p < .01$, and also a significant passing side effect, $F(1, 8) = 9.9$, $p < .01$.[5] The Passing Side × Passing Distance interaction almost met the standard significance level, $F(1, 8) = 4.9$, $p = .06$. Balls that would pass far behind the observer yielded the fastest responses. Observers took a little longer to judge balls destined to pass far in front of them. Even longer response times were seen for the balls aimed to land near the observer; the longest response times were for the balls going to pass in front of the observer. The ANOVA did not show significant effects of monocular as opposed to binocular viewing.

We examined whether the pattern of response times as a function of the passing side and passing distance was related to the temporal evolution of optical acceleration in the various conditions. Figure 2A shows the response times as a function of passing distance and passing side. An inverted-U-shaped relation between the response times and the passing position is apparent. Figures 2B and 2C present the time courses of image acceleration and image velocity ratio in the interval from 1 to 2 s after the ball started its approach. As mentioned previously, it is unclear how human observers detect acceleration. Here we considered two candidate variables. Image acceleration is the time derivative of image speed.

Table 1
Percentages of Correct Judgments and Mean Response Times of the Correct Responses in Experiment 1

Viewing	Near: Front	Near: Behind	Far: Front	Far: Behind
% correct				
Binocular	70	90	94	100
Monocular	58	86	90	96
Response time (s)				
Binocular	2.15	1.95	1.65	1.37
Monocular	2.02	1.88	1.73	1.36

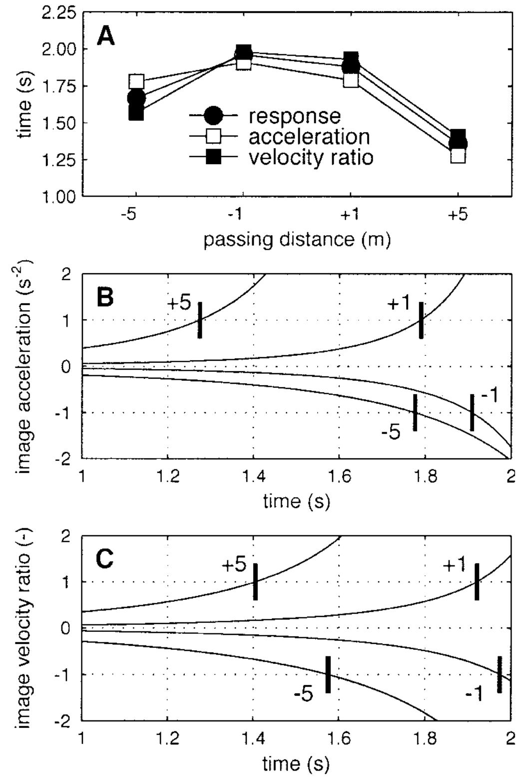

Figure 2. The judgment condition of Experiment 1: (A) Average response times, the times to reach a threshold of 1 s^{-2} of image acceleration, and the times to reach a threshold of 1 of the velocity ratio. (B) The optical acceleration profiles for the four ball trajectories. (C) The velocity ratio profiles for the same ball trajectories.

The image velocity ratio is the difference between image speed at time t and image speed at the start of the display, divided by the average image speed over that interval (cf. Babler & Dannemiller, 1993; Calderone & Kaiser, 1989). The time courses of these two variables are very similar, but there are differences. Indicated in Figures 2B and 2C are instants at which image acceleration reaches a value of 1 s^{-2} and instants at which the image velocity ratio reaches a value of 1, respectively. These threshold values were picked arbitrarily, but the patterns of times to reach both thresholds turned out to bear a strong relation to the recorded response times. This can be seen in Figure 2A, in which the square symbols represent the times to reach the threshold values indicated above. Both for image acceleration and image velocity ratio, the inverted-U shape resembles that of the actual response times. Note that taking different values for the thresholds would have little effect on the relative times to reach threshold (i.e., the pattern of times would be similar).

Catching task. To assess the success in the catching of the balls, we computed at each time step the distance between the

[5] One participant failed to give any correct responses on the five trials in which balls would pass in front at a near distance while viewing was monocular. Because of the resulting missing cell in the ANOVA on response times, this participant's data were not included in the significance tests.

wand and the center of the (virtual) ball. In a successful catch, this distance should be less than one ball radius at some moment. Inspection of the data showed that in only 9% of the trials did the distance fall below one ball radius. In another 15% of the trials, the minimum distance between ball and wand was twice a ball radius. Thus, in 76% of the trials, the distance between the wand and the ball was never smaller than two ball radii. We concluded that the participants were not successful in intercepting the virtual ball. To determine whether catching movements were somehow appropriate to the trajectory, we measured the position of the wand along the horizontal in the sagittal plane at the moment that the ball passed eye level. A repeated measures ANOVA on these wand positions, with factors of viewing (binocular vs. monocular) and passing side (in front vs. behind), showed that participants moved the wand on average 42 cm more forward when the ball passed in front of their initial position than when it passed behind their initial position, $F(1, 9) = 436.7$, $p < .01$. Thus, they moved the wand to different places in response to different ball trajectories but were not successful in actually intercepting these balls. Viewing effects were not significant.

Head movements. As illustrated in Figure 3, looking behavior in the judgment task differed from that in the catching task. Whereas participants' head movements tracked the ball in the catching task, there was very little head movement in the judging task. Figures 3A and 3C show results from a judging trial from 2 participants for balls aimed near the observer and balls aimed far from the observer, respectively. Figures 3B and 3D present data from the same participants trying to catch the virtual ball with the wand. The dashed lines represent the position of the ball image on the front wall of the CAVE as a function of time. Note that each panel depicts two trials, one in which the ball passes behind the observer (or, in the catching condition, behind the initial position of the catcher) and one in which the ball passes in front the observer (or in front of the initial position of the catcher). Furthermore, note that the ball image trajectory is the same in Figures 3A, 3B, and 3D. Figure 3C presents data from trials in which the ball was aimed far from the observer, a condition that was not included in the catching task. The solid lines in Figure 3 represent, as a function of time, the point on the front wall of the CAVE at which the participants would be looking if gaze angle followed head angle. Because we did not measure eye movements per se, we cannot draw conclusions about the point at the CAVE screen that participants were fixating, but Figure 3 clearly shows that tracking the ball in the catching task involved a significant amount of head rotation, whereas observers, when asked to judge the future passing side of the ball, either did not track the ball at all or tracked it almost exclusively with eye movements.

To assess the reliability of the observation that looking was different in the two tasks, we calculated the range of head rotation (elevation) by subtracting the minimum elevation angle from the maximum elevation angle for each trial. The average ranges by condition are presented in Table 2. (For a stationary observer, head elevation from looking straight ahead to looking at the top of the front CAVE wall would be about 41°.) A repeated measures ANOVA on the elevation ranges, with factors of viewing (binocular vs. monocular), task (judging near, judging far, and catching), and side (in front vs. behind), resulted in a significant task effect, $F(2, 18) = 90.5$, $p < .01$; a significant side effect, $F(1, 9) = 25.8$, $p < .01$; and a significant Task $\times$ Side effect, $F(2, 18) = 13.8$, $p < .01$. The side main effect can be understood from the difference in range of motion of the ball image across the CAVE screen. Balls aimed in front of the observer did not leave the screen, but balls projected behind the observer did. This was not necessarily true for the images of the ball in the catching condition because the projection of the ball was also a function of the participant's movement. However, in general, the range of motion of balls destined to land behind the initial catcher position was larger than the range of motion of balls aimed in front of the catcher's initial position. The significant task effect was the most interesting effect. Post hoc (Tukey's honestly significant difference [HSD]) tests showed that the elevation angle range in the catching condition

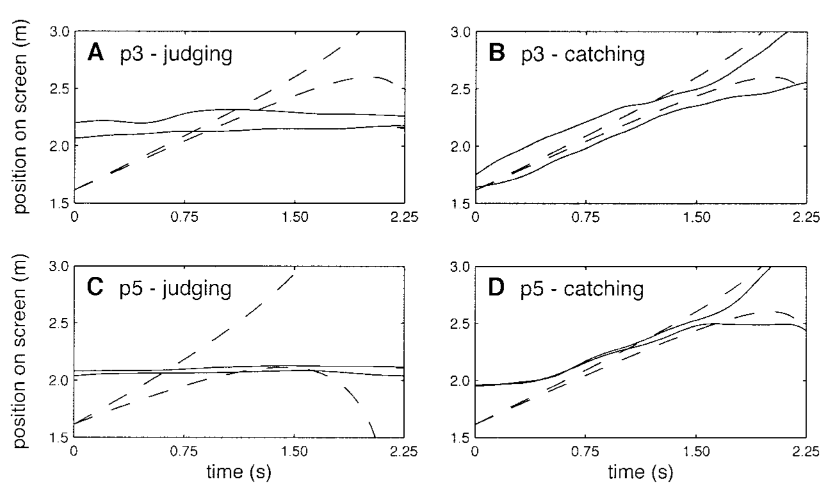

Figure 3. The positions of the ball image on the front wall of the Cave Automated Virtual Environment (CAVE; dashed lines) and the projections onto the front wall of the CAVE of 2 participants' (p3 and p5) head orientation (solid lines) in the judgment condition (Panels A and C) and the catching condition (Panels B and D) of Experiment 1.

Table 2
Average Ranges of Head Elevation (in Degrees) in Experiment 1

	Near		Far	
Viewing	Front	Behind	Front	Behind
Judging				
Binocular	13	15	12	15
Monocular	11	15	8	13
Catching				
Binocular	27	39		
Monocular	28	36		

was significantly larger than the elevation angle range in both the judging-near condition and the judging-far condition.

Discussion

Observers in the CAVE were able to indicate quite well whether a virtual ball would pass in front of them or behind them. Of the four possible passing locations, the balls that would pass at a short distance in front of them were the hardest to judge. The observers took more time to respond to these balls, but still their responses were correct less often.

The timing of the judgments was related to the specifics of the time courses of optical acceleration across the various conditions. This finding suggests that the timing of the responses was determined in large part by the time to reach some threshold value of "acceleration" (nonuniformity of image speed). We demonstrated this relation using two definitions of acceleration: image acceleration and image velocity ratio. The time courses of these two variables differ slightly, more so for some ball trajectories than for others (see Figure 2). If the response is based on reaching a fixed threshold level of either variable, these differences give rise to different predictions about when a response should be made. For instance, image acceleration increases faster than the image velocity ratio for the ball trajectory passing far behind the observer. Comparing the timing pattern of responses with the different predicted patterns could single out the particular variable that characterizes nonuniformity of optical speed as detected by human observers. This procedure could be expanded to evaluate other candidate variables. Two possibilities come to mind. First, the definition we used for the velocity ratio is still somewhat arbitrary—the difference in image speed at the moment of the response and at the start of the display, divided by the average image speed over that range. According to this definition, velocity ratio is the result of sampling image speed for 1.5–2 s in displays as used here. Alternatively, the sampling time might well be shorter than that. We might also expect the sampling time to be the same for the different trials. Second, one could allow for the delay between reaching some threshold value of some variable and the actual response. Different ranges might give different predicted patterns of response, thereby pinpointing the temporal range of the velocity ratio if used (see Michaels, Zeinstra, & Oudejans, 2001, for the application of a similar technique).

Catching virtual balls with the wand (hand) turned out to be very difficult, if not impossible, for our participants. On only a few of the trials did participants manage to get the wand close enough to the ball path to speak of a successful interception. The lack of success might have been due to the specific conditions chosen in the experiment. The virtual balls followed paths that passed at 1 m behind or in front of the initial position of the catcher's point of observation. In the judgment task, the balls that passed at a near distance in front of the observer were especially hard to judge. The errors in catching might be related to that finding. That is to say, ball paths that were identical in the two situations gave difficulties in both catching and judging.

There may be another reason for the difficulties experienced in catching that has to do with the differences between catching real balls and catching virtual balls in a CAVE. Because catchers have been shown to be able to catch luminous balls in the dark quite proficiently (Oudejans et al., 1999), the rather limited optical structure used in our CAVE experiments does not seem to be a logical explanation for the poor performance in our virtual-catching task. What is different in comparison to catching real balls, however, is that interception of *virtual* balls does not come with any haptic experience on how balls end up in the hand. Also, the choice to have the projection of balls stop after the virtual ball passed below eye level might have been unfortunate. This prevented the participants from seeing where a ball hit the ground or their body once they missed it. Not having this information might have resulted in a loss of calibration and no chance of recovery (cf. Bingham et al., 2000). Some participants reported that they had the impression that they were just waving their arms, not knowing how that movement related to where the ball was going. It may be that catching is not an exclusively visual enterprise but that haptics and perhaps acoustics provide crucial ingredients of the functional catching system as well. This calibration, however, applies to the final positioning of the hand to perform the actual catch. Participants seemed to be able to distinguish balls that were going to pass in front of them from balls that were going to pass behind them, but they had difficulty positioning the hand with adequate precision to actually intercept the virtual ball. Finally, optical acceleration, like many other variables, informs only of trajectory characteristics relative to the eye. It tells only whether the ball will cross the horizontal eye plane at, in front of, or behind the vertical eye plane; it does not specify the distance at which it will pass. Obviously, such information is needed to correctly position the wand.

One of the results we found most surprising was the difference in looking behavior between the judgment task and the catching task. Participants demonstrated significantly more head movement in tracking the ball in the catching condition than in the judging condition. (Because we did not register eye movements, we cannot exclude the possibility that balls in the judging condition were tracked with the eyes.) The disparity in looking behavior in the two tasks might have important implications for the generalizability of perception research to true perception-action. Apparently, judging virtual balls is a different task from actually catching those balls. It seems that the detection of optical information proceeds differently in the two tasks. If that is the case, the knowledge gathered from judgment studies might not be relevant for actual catching! For instance, knowing the thresholds for optical acceleration in a judgment task would be interesting in itself but might not be of much value to the student of action. The presumption that the two are equivalent is regularly made. For instance, Brouwer et al. (2002) asked observers to judge the acceleration of moving dots on a computer screen and found a threshold for detecting an image velocity ratio of approximately 25% (cf. Babler & Dannemiller, 1993, who also reported values of about 20%). Brouwer et al. compared the times to reach that threshold with the observed times at which expert catchers started to move to catch an approaching fly ball (Oudejans, Michaels, & Bakker, 1997). The first detectable head movements turned out to be earlier than the time at which image velocity ratio reached threshold, leading to the conclusion that the catching could not have been based on this specific optical variable.

But what if the thresholds in the catching situation were lower than the ones found by Brouwer et al. (2002) for judging? Suppose that the extraretinal signals coming from the vestibular system stimulated by the head rotations while tracking the ball in real catching—signals that are absent when engaging in a judgment task with negligible head movement—yielded a threshold lower than 20%–25%. If that were the case, the initiation of locomotion for catching fly balls could well be based on the very optical variable that Brouwer and colleagues discarded. Because we do not know the thresholds in a natural catching situation, conclusions as to the use of the image velocity ratio are unwarranted at present. A fair comparison may require the determination of thresholds under conditions that are representative for a real catching situation.

In summary, participants in the experiment did well in judging whether balls would pass behind or in front of them. They seem to have used some kind of optical acceleration variable to do so, but the small number of conditions and the specific organization of the experiment do not allow drawing this conclusion too firmly. In addition, it is not clear which particular variable was used in the judgments. Experiment 2 was designed to address both these issues. Finally, catching virtual balls with the wand turned out to be problematic for participants. We return to the actual interception of virtual balls in Experiment 3.

Experiment 2

Experiment 1 led to the tentative conclusion that the timing of the judgments could be predicted by the time courses of image acceleration and of image velocity ratio across the different conditions. This conclusion, however, was based on a rather small number of conditions. Further, the conclusion was based on a comparison of data across blocks of conditions in the experiment. Within a block of trials, balls in Experiment 1 always passed at the same distance, behind or in front of the point of observation. Potentially, response speed might have differed from block to block, interfering with the conclusions regarding the response times. A more powerful design would be one with a larger set of ball trajectories, all randomly presented within a block of trials. This is the approach that we took in Experiment 2, in which we attempted to replicate the relation between optical acceleration and the response times in judging the passing side of approaching virtual balls. Balls could come from one of two distances, could reach one of two heights, and could pass at one of three distances either in front of or behind the observer. This set of ball trajectories would lead to a set of predicted response times that are sufficiently specific to discriminate whether optical acceleration (image acceleration or the image velocity ratio) or "not-acceleration" variables (e.g., image position, image speed, image size, angular acceleration, angular speed, tangential speed) are used in this task. In addition, we hoped that mapping the actual response times onto the sets of response times predicted on the basis of image acceleration versus the sets of response times predicted on the basis of (various versions of) the image velocity ratio would allow us to find the proper characterization of optical acceleration (the change in optical speed) relevant to the human visual system.

Method

Participants. Eight volunteers, 4 men and 4 women (22–35 years of age), participated in the experiment.

Apparatus. The apparatus was identical to that used in Experiment 1. Due to software problems that we discovered after the data were collected, the sampling rate was approximately 50 Hz (instead of being about 100 Hz as in the previous experiment) for 7 of the 8 participants and approximately 100 Hz for the other participant.

Procedure and design. The combination of 2 initial ball distances (20 vs. 30 m) with 2 maximum heights (5.7 vs. 7.7 m) with 3 passing distances (1, 3, and 5 m) at both sides of the observer resulted in a total of 24 ball trajectories. These 24 trajectories were presented five times in a completely random order. The trials were presented in two blocks. The participants viewed the events binocularly in one block of 120 trials and monocularly in another block of 120 trials. Half of the participants started with the monocular condition; the other half started with the binocular condition. Each block of trials was preceded by a block of 10 practice trials in which balls came from a distance of 30 m, reached a maximum height of 7.7 m, and passed 5 m behind or in front of the observer. The instruction was the same as in Experiment 1. Observers were asked to press the appropriate button as soon as they knew where the ball would pass. They were instructed not to wait until a trial had ended but to try to be as accurate as possible. Other details of the experiment were identical to those of Experiment 1.

Results

The performance of the participants was variable. As indicated in column 2 of Table 3, the number of incorrect responses ranged from 2% to 27% of the number of trials. A repeated measures ANOVA on the percentage of correct responses, with factors of viewing (binocular vs. monocular), distance (far vs. near), height (low vs. high), and passing distance (−5, −3, −1, 1, 3, 5 m; negative numbers indicate balls passing in front of the participant), resulted in a significant passing distance effect, $F(5, 35) = 10.3$, $p < .01$. The closer to the participant the balls passed, the fewer correct responses were seen. The ANOVA indicated two significant interactions that both concerned differences among the balls that passed 1 m behind the observer. A significant Distance × Passing Distance effect, $F(5, 35) = 5.1$, $p < .01$, indicated that, for these balls, more errors were made when they came from the far distance than when they came from the near distance. Analogously, a significant Height × Passing Distance effect, $F(5, 35) = 2.7$, $p < .05$, indicated that more errors were made when these balls traveled the lower path than when they traveled the higher path. The ANOVA did not yield any other significant main or interaction effects.

Table 3 also gives the average response times (i.e., the intervals from the first ball movement until the response) for the individual participants. A speed–accuracy trade-off is apparent; participants who waited longer before giving a response made fewer errors (a regression of the percentage of correct responses onto the average response times resulted in an R^2 value of .74). Response times also differed across conditions. The times were analyzed with an

Table 3
Percentages of Correct Responses, Average Response Times (RT), and Variance in RT Accounted for by Different Predictors in Experiment 2

			Acceleration			Velocity ratio		
Participant	% correct	RT (s)	Monocular	Binocular	All	Monocular	Binocular	All
1	96	1.71	.52	.63	.56	.56	.73	.64
2	93	1.61	—	.07	—	.11	.22	.15
3	88	1.20	—	—	—	—	—	—
4	86	1.26	—	—	—	—	—	—
5	73	1.18	—	—	—	—	—	—
6	97	1.87	.70	.73	.69	.58	.70	.61
7	98	1.84	.51	.56	.49	.63	.55	.54
8	91	1.61	.32	—	.15	.42	.24	.31

Note. Dashes indicate R^2 values that are less than zero.

ANOVA analogous to that done on performance.[6] No viewing effect was found, but all other main effects were significant. Responses were earlier when balls came from the closer distance, $F(1, 4) = 73.9$, $p < .01$; when they traveled the lower path, $F(1, 4) = 30.4$, $p < .01$; and when passing distance was farther away, $F(5, 20) = 9.1$, $p < .01$. Also, a number of interaction effects were significant: Distance × Height, $F(1, 4) = 30.0$, $p < .01$; Distance × Passing Distance, $F(5, 20) = 23.6$, $p < .01$; and Height × Passing Distance, $F(5, 35) = 9.0$, $p < .01$. Instead of giving full details of these interactions, we address their presumed origins in terms of the temporal evolution of a number of optical variables.

The time courses of the optical variables that we considered differed across conditions. The left column of Figure 4 presents each of these variables as a function of the time after the ball had started its approach. To reiterate, image position is the projection of the ball onto an image plane, and image speed is its derivative with respect to time (see Figure 1). Image acceleration is the temporal derivative of image speed, and image velocity ratio is the difference in image speed at each point in time and image speed at the start of the ball approach, divided by the average image speed over that interval. Image size is the size of the ball projection on the image plane. Finally, tangential speed, angular speed, and angular acceleration are the speed of the ball orthogonal to a line connecting eye and ball, and the angular speed and acceleration of this line, respectively (tangential speed and angular acceleration are variables considered by Brancazio, 1985).

The middle and right columns of Figure 4 show the same variables but now as a function of the time (averaged over trials and viewing conditions) before the response was given for each ball trajectory. The data used to prepare this figure were from Participants 6 and 7, two of the best performing participants (see Table 3). A first criterion to evaluate the variables with respect to their possible use by the observers is in the degree of convergence of the lines in the latter two columns. If judgments were based on the reaching of some value of one of the variables, and delays to respond after reaching this criterion were relatively constant, the lines should converge (see Michaels et al., 2001). Second, because observers were to make a categorical judgment, we would expect to see two bundles of lines, each mapping onto one of the two situations. Image size does not meet these criteria and can, thus, be ruled out as the variable for the judgment of passing side.

Inspection of Figure 4 also allows the elimination of image position and tangential velocity as variables used for judging passing side. The image-position traces start as a single band of traces that splits into two bands of traces toward the time of response. The lower bundle represents balls passing in front of the observer, and the higher bundle represents the balls passing behind the observer. If judgments had been based on reaching a threshold value of optical position, all image-position traces of each bundle would intersect a horizontal line at the threshold value: a higher line for the balls passing behind the observer and a lower line for the balls passing in front of the observer. Furthermore, these lines should be passed only once. Whereas the traces representing the balls passing behind the observer meet these criteria, the traces representing the balls passing in front do not. For this latter group of traces, no threshold values can be found that are passed by *all* traces. Analogously, tangential velocity can be ruled out as a variable useful for judging passing side for the same reasons. Some might argue, however, that an alternative strategy would allow for, for instance, image position to be used for judging the future passing side of the balls. Observers might have judged ball trajectories that led to images that reach the higher regions of the screen (or images that actually leave the screen) as passing *behind* and, consequently, all other trajectories as being *in front*. We return to this argument after we have introduced an analysis of the temporal spread of the traces, the results of which provide part of the arguments against this explanation.

Given that we discarded image position, image size, and tangential velocity as operative variables, we are left with five candidate variables. A final criterion renders three of these variables as unlikely candidates, leaving image acceleration and the image velocity ratio as the variables most probably used in the judgments. This final criterion is the amount of convergence of the traces of these optical variables. We expect that the spread of lines along the time axis at the moment of reaching the threshold value would be small for the optical variable that is actually used. That is to say, we expect that the traces, after aligning them with the times of

[6] Three participants did not give any correct responses in one of the conditions. As a result, significance tests are based on the data of the 5 remaining participants.

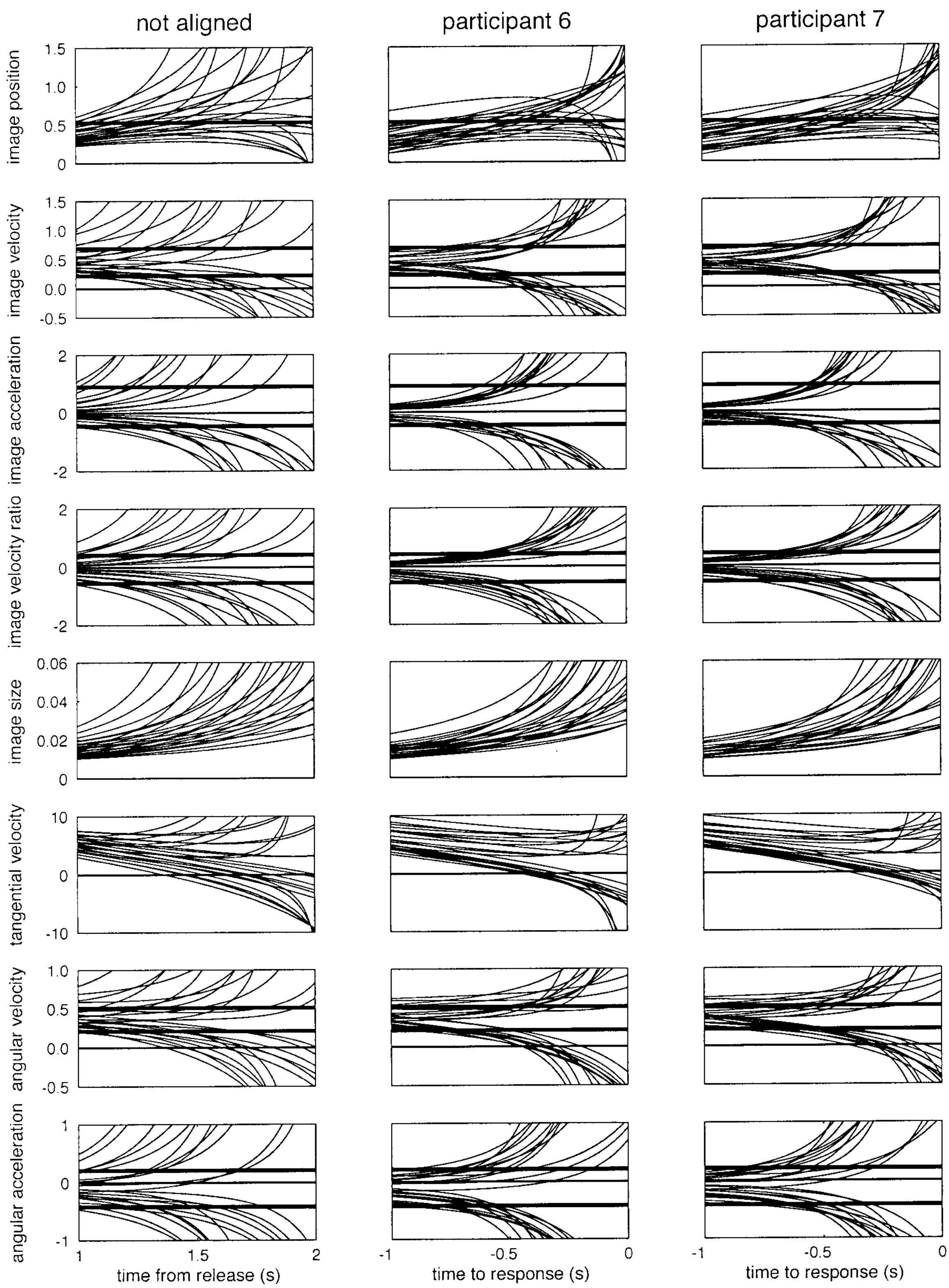

Figure 4. Different optical variables as a function of the time after the start of ball approach and as a function of the time before a response was made for 2 participants in Experiment 2 (Participants 6 and 7). Also indicated are the intersubject averages of the thresholds determined with the temporal convergence analyses reported in Table 4.

response (the middle and right columns of Figure 4), come together at the moment of reaching threshold value. Thus, a comparison of this spread among variables would enable the identification of the most promising candidates. We used a measure that we called *temporal convergence* (TC) to compare optical variables. A complication in comparing optical variables is the fact that we do not know the threshold value at which we should measure the temporal spread in the traces of the different conditions. The most straightforward method to search for that threshold value would be to compute temporal spreads for different threshold values and to search for a minimum in those values of temporal spread. Graphically, this would amount to drawing two horizontal lines in each panel in the middle and right columns of Figure 4 and shifting these lines up and down such that the band of intersecting lines of the temporal evolution of each optical variable would be minimally narrow. The narrowness of the band would be a measure of temporal spread, and the position of the line would indicate the threshold value at which the temporal spread would be minimal. Unfortunately, this method did not yield reliable results with our data.

The alternative method that we used was based on the fact that we can assume that responses are given after the threshold has been reached. In the analysis, which was performed for each participant for each optical variable, we first identified the two groups of trials—of balls passing behind and in front of the observer—including only trials with correct responses. Next, for each group of trials, we determined the value of the variable (threshold) at the lower 95th percentile of the response times (note that Figure 4 displays traces computed with response times averaged per condition, but the analysis was performed on the raw data). In other words, we determined the time after which 95% of the responses fell and its associated threshold values for the variables that we considered. Finally, again for each group, we computed the standard deviations of the time from reaching those thresholds until the response. These standard deviations were our measure, TC, of the spread over time of the traces in Figure 4 or, more to the point, our measure of how well each variable predicted the response times. Note that because the TCs for all variables are in the same units—seconds—they are directly comparable. The optical variable with the smallest TC is implicated as being the variable most likely used in judging future passing side.

Table 4 presents the average thresholds and TCs for both the group of trials with balls passing behind the observer and the group of trials with balls passing in front for all five optical variables considered. A repeated measures ANOVA on the TCs, with factors of variable (image acceleration, image velocity ratio, angular acceleration, image velocity, and angular velocity) and side (in front vs. behind), indicated a significant variable effect, $F(4, 28) = 12.0$, $p < .01$, as well as a significant Variable × Side interaction, $F(4, 28) = 10.1$, $p < .01$. As to the variable main effect, Tukey's HSD post hoc tests revealed that the TCs of image acceleration and image velocity ratio were not significantly different from each other but were significantly smaller than the TCs of the other three variables (see Table 4). The interaction reflected the larger differences among variables for balls passing behind than for balls passing in front.

We previously discussed the possible use of image position in the judgment of future passing side. The extreme version of this strategy would capitalize on the fact that the projections of balls that were to pass behind the point of observation always left the front projection screen, whereas the images of balls that were to pass in front of the point of observation remained on the screen. The perceiver's job would simply be to ascertain which balls will leave the front screen. This strategy, however, does not explain our results in at least two ways. The first problem is that this strategy cannot explain the pattern in the timing of the responses to balls that will pass in front of the point of observation because, according to the strategy just sketched, the decision to judge a ball as one that will pass in front of the observer is contingent on the conclusion that the ball will not pass behind the observer. On the basis of what criterion does one decide that a ball image is not going to leave the front projection screen? The threshold of image position for balls destined to pass behind the point of observation, estimated in Table 3, would not fit the job (see Figure 4). This threshold would render a few of the trajectories of balls passing in front of the point of observation to appear as balls that are going to pass behind the point of observation. Our data do not show the resulting systematic judgment errors, which strengthens our conclusion, based on the other arguments that we gave above, that image position was not the variable used by our observers.

As mentioned previously, if image acceleration or image velocity ratio were used in the judgments, the aligning procedure should result in overlapping lines, at least in the region of the supposed threshold value. This is roughly what we see in Figure 4 for most of the image-acceleration traces and most of the image-velocity-ratio traces. A few outliers can be seen, however. In each panel, three traces seem to lie a little to the right of the majority of traces. These traces are from balls that came from a short distance,

Table 4
Intersubject Averages of Thresholds of Different Optical Variables and Their TCs (in Seconds) for the Correct Trials in Experiment 2

	Front		Behind	
Variable	Threshold	TC	Threshold	TC
Image acceleration	−0.45 (0.50)	0.33 (0.08)	0.90 (0.92)	0.25 (0.07)
Image velocity ratio	−0.55 (0.60)	0.30 (0.06)	0.42 (0.30)	0.25 (0.06)
Angular acceleration	−0.42 (0.39)	0.34 (0.09)	0.21 (0.17)	0.38 (0.15)
Image velocity	0.22 (0.17)	0.40 (0.16)	0.69 (0.23)	0.32 (0.12)
Angular velocity	0.21 (0.16)	0.34 (0.12)	0.51 (0.10)	0.48 (0.10)
Image position			0.53 (0.17)	0.24 (0.05)

Note. Numbers in parentheses are standard deviations. TC = temporal convergence.

reached the higher maximum height, and passed behind the observer. For balls that pass behind, images always leave the CAVE front screen at some point in time. The conditions in which the outliers appeared are among the conditions in which the vanishing of the ball image happens the shortest times after ball release.

Apart from these outliers, image acceleration and the image velocity ratio emerge as variables possibly exploited in making judgments about the future passing side of an approaching fly ball. We now attempt to further discriminate the predictive power of these variables. On the assumptions that timing of responses is related to reaching a threshold and of a specific threshold value, predictions can be made as to when responses should have been given in each condition. Table 3 shows, for each participant, R^2 values of regressions of the response times onto two sets of predicted response times. One set of predicted response times was calculated on the basis of the time at which image acceleration reached a specific threshold value; the second set of predicted response times were those at which the image velocity ratio reached a specific threshold value. Using a minimization procedure, we searched for the threshold that resulted in the highest R^2 values for each participant for each variable separately. Furthermore, because we expected that the delay between reaching a threshold of either variable and the actual response was constant within each participant's data, we forced the slopes of the regression equations to be 1. As a result, R^2 values could be less than zero, which are reported as dashes in Table 3. The regressions were performed on the trials with correct responses. A comparison of these goodness-of-fit measures with the number of correct responses of each participant shows that the more successful the participants, the stronger their responses were related to image acceleration and image-velocity-ratio thresholds. In particular, Participants 1, 6, and 7 had few incorrect responses as well as high R^2 values in the regressions. Unfortunately, these analyses did not favor one of these optical variables over the other.

Discussion

The results in the judgment task of Experiment 1 led us to believe that the timing of the responses was related to reaching a threshold value of a change in image speed, although we could not tell the exact identity of that variable, in part because of the small number of conditions and the blocking of conditions. Experiment 2 was designed to provide a better test of whether change in optical speed is the relevant variable and possibly to get a clearer picture of the best characterization of that variable. For those purposes, we asked observers to judge the landing destination of a wide variety of approaching balls. The use of different release distances and different maximum heights would also allow us to eliminate variables as the basis for the judgments.

Performance in the task was somewhat variable over observers. Observers who waited the longest to give their answers made the fewest errors. The timing of the responses of the best performing participants was also more strongly related to acceleration than was the timing of the responses of those who performed less well. In addition, the TC dependent variable indicated that the spread of the image acceleration and image-velocity-ratio traces was smallest after aligning these with the response times. Thus, the results seem to argue that the judging of the landing location of fly balls is, indeed, on the basis of the change in image speed. Still, a few issues remain. First, the results did not distinguish whether acceleration or velocity ratio was the better characterization of the change in image speed as detected by the human visual system. We return to this issue later. Second, we also noticed three acceleration outliers in Figure 4. These outliers were not random; they were present in both participants' data and constituted the complete set of trials simulating balls coming from a distance of 20 m, reaching a maximum height of 7.7 m.

One explanation is that the outliers could be the result of one of the more mundane problems in the CAVE. The CAVE that we used in our experiments has no ceiling projection screen. That means that the projected image of balls that pass behind a stationary observer moved off the front screen at some point during their flight. If the CAVE had had a ceiling, the ball projection would have continued its travel across that ceiling, but in the absence of a ceiling projection, the ball image simply vanished. This, of course, was true for all the balls passing behind the observer. However, the balls coming from a near distance traveling a high path were among the fastest to leave the front screen. These balls might have left the CAVE front screen too quickly for a proper judgment to be made. Of course, because balls leaving the front screen would pass behind the observer, judgments could still be correct when based on this fact. Thus, the experimental setup might have required observers to use two types of information—change in image speed and the vanishing of images—the latter of which cannot be used in natural ball catching.

In sum, the results reported in Tables 3 and 4 and in Figure 4 led us to conclude that acceleration (i.e., the change in image speed) is implicated in the judgment of the passing side of fly balls, but we cannot yet say what variable would capture that acceleration. The situation is more complex than a mere choice between two candidate variables. First, we have not considered any delay between reaching a threshold and the actual button press (the judgment as we measured it). Second, in the definition of the image velocity ratio, we made an additional choice (cf. Babler & Dannemiller, 1993; Calderone & Kaiser, 1989). We defined velocity ratio as the change in image speed from the start of the trial divided by the average image speed over that interval. This yielded intervals well over 1 s in duration. Finally, the intervals were of different duration for all conditions. Alternative assumptions might be a constant interval for sampling optical speed and one that is shorter than 1 s.

We devised several methods that we hoped would help define the proper acceleration variable. To investigate the potential effect of a delay between reaching a threshold value of image acceleration and the actual response, we computed regression equations using predicted response times based on reaching thresholds at different time intervals before the response was given. Again, the slope in the regression equations was forced to be 1, and we considered the threshold values that gave the highest R^2. Similarly, we varied delay times between reaching a threshold and the actual response as well as the time interval over which the image velocity ratio was defined. We hoped to find a clear peak in the collection of R^2 values that would indicate the proper variable (acceleration vs. velocity ratio, and for the latter, the proper interval size) together with the proper value of the delay. Unfortunately, the method could not distinguish the two acceleration variables because the different sets of predicted response times were so highly correlated that differences in R^2 values of the fits were minimal. If one thinks about this method as spanning a landscape of candidate variables and their predictive value and that the task at hand is to find a maximum in this landscape (which was, in fact, one of the implementations of the method we used), then the peaks in the landscape were too low to allow firm conclusions. For this method to be successful, extra care must be given to keeping correlations between sets of predicted response times low.

Experiment 3

Experiment 3 was designed to expand on the different aspects of the findings of Experiments 1 and 2. We had participants perform both a judgment task and an interception task. The judgment task found its rationale in Experiment 2. Although the results of this experiment pointed in the direction of change in image speed, performance was rather variable across participants. The lack of feedback might have encouraged some participants to make decisions too early, yielding misjudgments. Because the participants were not aware of these misjudgments, they could not adapt their judgment timing. In addition, in Experiment 2, we found a subset of the trials that yielded apparent outlying behavior, possibly due to the absence of a ceiling projection screen in the CAVE and the consequent disappearance of the ball image early during a trial. To investigate whether the outliers were bona fide departures from the use of optical acceleration or mere ceiling artifacts, we attempted to replicate Experiment 2 with two changes. First, participants received information about the ball's landing side after each trial, allowing them to evaluate their judgments. Second, we had participants judge the same set of trials while standing close to the front screen in the CAVE as well as standing far from the front screen of the CAVE. Because the position of the observer relative to the projection screen determines the details of the projection on that screen, the distance manipulation affects the timing and incidence of ball projections leaving the front screen.

The interception task was inspired by the findings of Experiment 1. In that experiment, we asked participants to try to intercept the virtual balls using the wand, the hand-held input device in the CAVE. Overall, they were not able to do so successfully. One possible reason for the difficulty they encountered might have been the lack of feedback in the virtual situation. Normally, when a ball is caught, it is felt in the hand(s). When the ball is just missed, it might still have touched the hand. And, in other cases, it would hit another part of the body or the floor. In contrast, things just disappear in virtuality. In addition, optical acceleration, as noted earlier, specifies only whether the ball will cross the eye plane in front of or behind the eye; it does not specify the distance at which it will pass. Obviously, such information is needed to correctly position the wand. To try to overcome these limitations, we asked participants to intercept the virtual balls with their foreheads instead of with the wand. The idea was that a successful interception would result in noticeable looming of the optical image, providing the participant with the feedback that was lacking when intercepting with the wand.

A second potential problem of the interception task of Experiment 1 was the short range for locomotion. Virtual balls would pass 1 m behind or in front of the initial point of observation. Arm movement alone could have been almost enough to get the wand at the interception location. Changing the task to interception with the forehead forces the participant to locomote to intercept the same balls. In addition, we also increased the range of passing distances by having participants always start in the back of the CAVE and having balls always pass in front of that initial position. The drawback of this choice, of course, is that we were not able to distinguish locomotion to balls going to pass in front of the catcher versus locomotion to balls going to pass behind the catcher. This choice has also been made in the past to prevent participants from tripping over equipment wires (Oudejans, Michaels, Bakker, & Dolné, 1996).

Method

Participants. Eight participants (6 men and 2 women, ages 21–37 years) were paid 25 Dutch guilders (U.S.$13) for their participation in the experiment.

Apparatus. The apparatus was identical to that of Experiment 1.

Procedure and design. Participants in this experiment performed a judgment task and an interception task, in that order. The judgment task, in most respects, was identical to that in Experiment 2. Differences were the following: First, participants were standing at a different location in the CAVE. Whereas observers in Experiment 2 were always standing in the center of the CAVE, observers in Experiment 3 were standing either 0.75 m in front of the center of the CAVE or 0.75 m behind the center of the CAVE. (On the practice trials, observers stood at the center.) At both locations, observers received two blocks of 72 trials, with three repetitions of trials that differed in starting distance (20 m vs. 30 m), maximum height (5.7 m vs. 7.7 m), passing distance (1, 3, and 5 m), and passing side (front vs. behind). The first block of trials was intended to train the participants to maximize their performance, and the second block of trials consisted of the actual test trials. The following analyses involved only the test trials. Second, we ran the CAVE software in the cyclopean mode. In this mode, CAVE images are computed with reference to a point between the two eyes, and no stereo effect occurs with the synchronized presentation of images to the left and right eyes. Third, observers received feedback on the correct answer; after the judgment had been made, the experimenter informed the participant as to the side on which the ball had passed. Fourth, projection of the ball stopped after passing floor level instead of after passing eye level.

After performing the judgment trials, the participants were given interception trials. The instruction to the participant was to intercept the virtual ball with the forehead. At the start of the trial, the participant positioned himself or herself onto a white circle, the center of which was located at 1.25 m behind the center of the CAVE floor. After a ready signal from the participant, the ball was shown at its starting position. After a second signal from the participant indicating that he or she saw the ball, the ball started its approach. The participant tried to intercept the ball with the forehead. Finally, he or she reported whether the interception had been successful and where the ball had hit the body or where it had passed. Balls could come from one of two starting distances (30 vs. 40 m), reach one of two maximum heights (4.7 vs. 5.7 m), and were aimed to pass at one of three distances in front of the initial position of the point of observation (0.5, 1.0, and 1.5 m).[7] This part of the experiment consisted of three blocks of trials. The first block included 6 practice trials, with two repetitions of the trials with each of the passing distances but always with the 30-m starting distance and the 4.7-m maximum ball height. The practice trials were followed by two blocks of 36 experimental trials, each with three repetitions of each condition in a completely random order. As in the judgment condition, the events were viewed with two eyes in the cyclopean CAVE mode.

Results

Judgment task. Table 5 gives the percentage of correct responses together with the average response time for each partici-

[7] Because participants started each trial standing in the back of the CAVE, the set of ball trajectories used in the judgment task would result in ball images disappearing off the screen in a large fraction of the trials. By increasing the initial distance and decreasing the height of the paths, we avoided this.

Table 5
Percentages of Correct Responses, Average Response Times (RT), and Variance in RT Accounted for by Different Predictors in Experiment 3

Participant	% correct Front	% correct Back	RT (s)	Acceleration Front	Acceleration Back	Acceleration All	Velocity ratio Front	Velocity ratio Back	Velocity ratio All
1	96	96	1.59	.61	.23	.40	.67	.53	.54
2	100	96	1.59	—	.24	.08	.43	.35	.33
3	97	96	1.50	—	.08	.01	.22	.45	.34
4	99	97	1.67	—	.55	.32	.39	.57	.49
5	99	97	1.39	.05	—	—	.11	.11	.10
6	97	93	1.72	.27	.49	.37	.31	.43	.35
7	93	94	1.27	—	.04	—	—	.15	—
8	99	96	1.66	.15	.45	.26	.34	.65	.43

Note. Dashes indicate R^2 values that are less than zero.

pant's two viewing conditions. Table 5 shows that observers were quite successful in their judgments. Slightly lower percentages of correct responses were given when participants were standing in the back of the CAVE, $t(7) = 2.5$, $p < .05$.

The manipulation of the position of the observer was inspired by the apparent outliers in Figure 4, which, we speculated, were due to the disappearance of the ball's projection from the screen. Figure 5 shows analogous acceleration traces for one of the participants in Experiment 3. When the participant stood in the back of the CAVE, three outliers can be seen in Figures 5B and 5E. Two of the three outlying traces were, as in the previous experiment, from the balls coming from 20 m away, reaching their highest point at 7.7 m, and landing behind the observer. The other outlier was from the balls launched 20 m from the observer, flying the low path, and landing 1 m behind the observer. Thus, this figure seems to support the thesis that the timing of the disappearing ball projections is, at least in part, responsible for the observed outliers. Inspection of analogous figures of the other participants, however, did not suggest a strong role of observer position. In some cases, the same outliers were seen, in some other cases the outliers were also present in the front condition, and in still other cases no outliers were apparent.

Given that participants in this experiment were quite successful in their judgments, we would expect that the analysis of the degree of convergence of the traces of the different optical variables would reveal a clearer picture than did the data of the variably performing participants of Experiment 2. Table 6 presents the thresholds and TCs calculated in this analysis. A repeated measures ANOVA on the TCs, with factors of variable (image acceleration, image velocity ratio, angular acceleration, image velocity, and angular velocity) and side (in front vs. behind), revealed a significant effect of side, $F(1, 7) = 8.6$, $p < .05$; a significant variable effect, $F(4, 28) = 16.1$, $p < .01$; and also a significant Variable × Side interaction, $F(4, 28) = 24.9$, $p < .01$. Tukey's HSD post hoc tests indicated that TCs were smaller for balls passing in front of the observer than for balls passing behind and smaller for image acceleration and image velocity ratio than for the other variables.[8] The variable effect was stronger for balls passing behind than for balls passing in front.

In line with our findings in Experiment 2, image acceleration and image velocity ratio turned out to be the most promising candidate variables for judging passing side. We went on to perform the regressions of the response times onto response times predicted on the basis of reaching threshold values in these two variables (see Table 5). The R^2 values are comparable to those in Experiment 2 (cf. Tables 3 and 5) for most participants but are still low for some others. Again, faster responses seemed to go together with more incorrect responses and with poorer fits. Also, there were no apparent differences in the quality of fits between the two optical variables being considered.

Interception task. We assessed the success of interception by comparing the position of the sensor attached to the LC glasses to the known coordinates of the virtual ball along its trajectory. As in Experiment 1, a potential disadvantage of comparing these coordinates lies in their temporal and spatial resolution and the potential errors resulting from their different frames of reference (i.e., the ball coordinates are defined in the frame of reference for CAVE projection, and the movement registration uses its own frame of reference. Ideally, the two frames of reference coincide, but there are always discrepancies between the two). We compared the outcome scores of the verbal reports with the outcome scores of an algorithm that used the ball coordinates and the position data of the Flock-of-Birds sensor attached to the LC glasses as input. We defined an elliptical surface around a point between the two eyes. The horizontal radius of this ellipse was set at 7.5 cm, and the vertical radius at 4.0 cm. An interception was defined to have occurred if at any point during the trial, any point of the 20-cm virtual ball had touched this elliptical surface, which represented the forehead. The algorithm agreed with the verbal reports in 88% of the trials, leading to a Cohen's kappa of .75.

Participants successfully intercepted 47% of the virtual balls projected at them (43% in the first block of test trials and 51% in the second block of test trials), $t(7) = 3.29$, $p < .05$. Table 7 presents the average percentage of successful interceptions for each condition separately. The table suggests that balls destined to pass the participant at different distances were intercepted at approximately the same rate. With the possible exception of balls

[8] Differences among image acceleration and the image velocity ratio on the one hand and angular acceleration, image velocity, and angular velocity on the other hand were significant at the $p = .05$ level except for the difference between image acceleration and image velocity, which had a chance of a Type I error of .052.

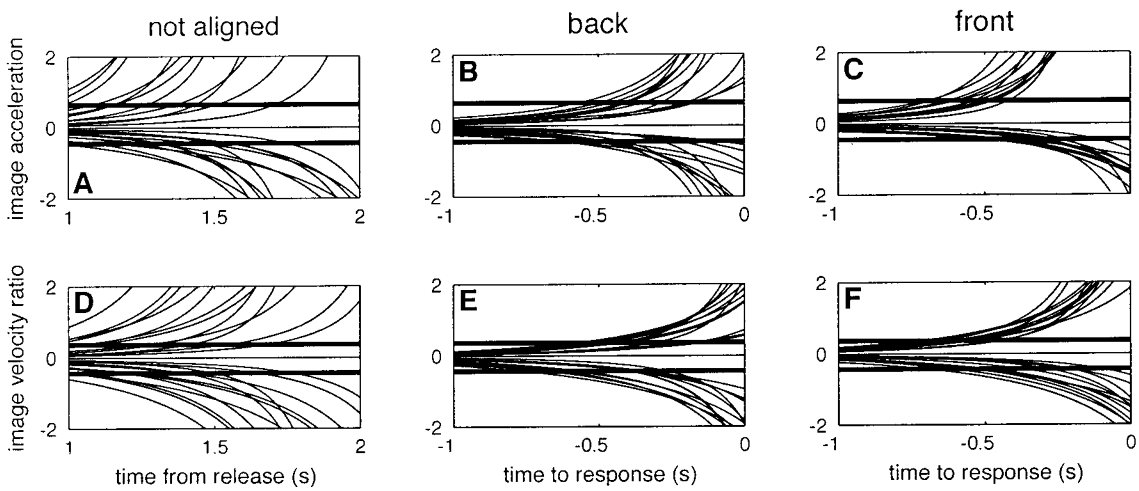

Figure 5. Optical acceleration as a function of time after the start of ball approach (A) and the time until a judgment was made for 1 participant in Experiment 3, standing in the back position (B) and in the front position (C), and the velocity ratio as a function of the time after the start of ball approach (D) and as a function of the time until a response was made for the same participant, also in the back position (E) and in the front position (F). Also indicated are the intersubject averages of the thresholds determined with the temporal convergence analyses reported in Table 6.

coming from a near distance, flying the high path, and destined to pass farthest from the initial catcher location, all balls seemed quite easy to intercept.

Predictably, the participants initiated their locomotion in a forward direction in a majority of cases (97% of all trials). Table 8 gives the locomotion initiation times, averaged across the successful interceptions of all participants, for each condition. The locomotor responses were considerably earlier than the judgment responses (cf. Tables 5 and 8). Further, over the course of the experiment, participants waited longer before initiating their movement. For successful interceptions, movement initiation time was 0.85 s on the first block of trials and 1.04 s on the second, $t(266) = 4.1$, $p < .01$. Finally, given that participants did not need to determine response direction, it is not surprising that a comparison of response times with those predicted from acceleration profiles showed that the ordering of movement initiation times could not be explained by the pattern of acceleration traces.

Whereas the timing of movement initiation did not seem related to particulars in image acceleration or in the image velocity ratio, participants' locomotion demonstrated that they did move so as to keep optical speed constant. Figure 6 illustrates this point in two examples, one of a successful interception (Figure 6A) and another of an unsuccessful interception (Figure 6B), both by the same participant. Depicted are the optical position of the ball to the catcher if he or she were to stay at the initial position in the CAVE (dashed lines) and the optical position of the ball to the moving catcher (solid lines), both as a function of time (cf. Michaels & Oudejans, 1992). Clearly, the line representing optical position to the moving catcher stays straight for a longer period, implying that optical speed is constant.

Discussion

Providing participants with feedback about the correct choice in the judgment task improved the success rate of their judgments. Whereas many of the observers in Experiment 2 were rather inaccurate, all observers in the current experiment performed quite well. In Experiment 2, the success in judgments was related to the

Table 6
Intersubject Averages of Thresholds of Different Optical Variables and Their TCs (in Seconds) for the Correct Trials in Experiment 3

Variable	Front		Behind	
	Threshold	TC	Threshold	TC
Image acceleration	−0.45 (0.20)	0.26 (0.08)	0.64 (0.34)	0.22 (0.03)
Image velocity ratio	−0.43 (0.26)	0.24 (0.03)	0.37 (0.15)	0.23 (0.02)
Angular acceleration	−0.32 (0.13)	0.30 (0.07)	0.14 (0.08)	0.40 (0.08)
Image velocity	0.26 (0.08)	0.31 (0.14)	0.67 (0.13)	0.31 (0.14)
Angular velocity	0.21 (0.07)	0.22 (0.05)	0.49 (0.06)	0.55 (0.07)
Image position			0.53 (0.09)	0.22 (0.05)

Note. Numbers in parentheses are standard deviations. TC = temporal convergence.

Table 7
Percentages of Successful Interceptions in Experiment 3 for Balls Coming From Shorter and Longer Distances, via Low and High Trajectories and Passing at Different Distances

Passing distance (m)	Shorter distance		Longer distance	
	Low	High	Low	High
0.5	50	63	46	44
1.0	67	33	60	48
1.5	33	21	56	40

average response time: Successful participants waited longer to respond. The response times of the observers in the current study were comparable to those of the successful observers in the previous experiment. Thus, perhaps not surprisingly, the conclusion must be that feedback helped the participants to get attuned to the information in this task. Although at first this finding might seem to be a trivial one, it certainly stresses the fact that the feedback available in normal situations is not always available in virtual reality, or, for that matter, in many setups for psychophysical studies. In the CAVE, one simply does not feel balls in the hand or hear balls bounce against the floor. We offered a surrogate feedback, which helped the participants, but still, this is different from the natural situation.

The lack of feedback might have been even more critically important in the interception of (virtual) balls. When we asked participants to "catch" virtual balls with the wand in Experiment 1, they were not able to do so successfully. Many of them reported that they were not sure that their actions were appropriate. When the task was interception with the forehead, the number of successful trials was dramatically higher. About 50% of the balls were caught by our participants, which approaches the percentage of successful catches that Oudejans et al. (1999) reported (60%–70%) for their conditions with luminous balls in pitch dark. Furthermore, participants in our study, after some practice, seemed to know quite well where balls had gone. They were able to report whether balls had gone over their head, collided with their forehead, touched their shoulder, and the like. The feedback in this task was not haptic, as in natural situations, but completely visual. Balls hitting the forehead gave rise to looming of their optical contour, which apparently sufficed to distinguish a successful interception from an unsuccessful one. Still the task was rather difficult. More research would be needed to pinpoint the difficulties. Possible

Table 8
Average Response Times (in Seconds) of the Successful Interceptions in Experiment 3 for Balls Coming From Shorter and Longer Distances, via Low and High Trajectories and Passing at Different Distances

Passing distance (m)	Shorter distance		Longer distance	
	Low	High	Low	High
0.5	0.98	1.31	1.03	0.94
1.0	0.88	0.80	0.90	0.83
1.5	0.86	0.88	0.90	0.95

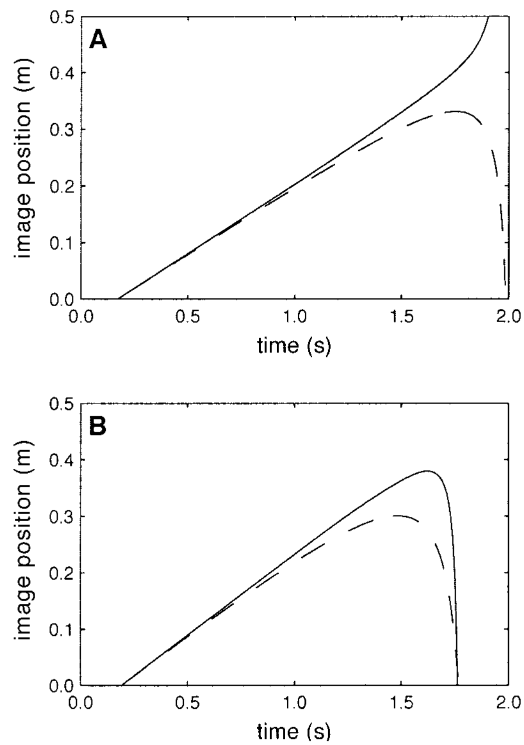

Figure 6. Optical position as a function of time after the start of ball approach for (A) a successful interception and (B) an unsuccessful interception by the same participant in Experiment 3. Solid lines depict optical position computed with respect to the moving point of observation. Dashed lines depict optical position computed with respect to the point of observation at its initial position.

contributors to the difficulties might include the length and organization of the practice period, the setting—catching luminous balls in the dark—with its lack of a structured visual background and the limited amount of light, and the potential problems created by a catcher stepping forward too early. The latter effect was seen in novice ball catchers (Oudejans et al., 1997); in the CAVE this could result in ball projections leaving the front screen. We investigated this issue in the context of the judgment task and found that judging was less successful when participants were standing in the back of the CAVE than when they were standing closer to the front screen, where ball projections never left the screen.

The timing of the responses in the judgment task replicated the findings in the earlier experiments. For most participants, the timing pattern was predicted by the times that image acceleration or image velocity ratio reached some threshold value. This was not the case for the interception task. First, these initiation times were much faster than the response times in the judgment task (cf. Oudejans et al., 1999). Second, the pattern in initiation times did not appear to be related to acceleration profiles. If these initiation times had been based on image acceleration or on image velocity ratio, there would have been a specific ordering of initiation times across conditions (analogous to the pattern of response times in the judgment task). For instance, balls aimed to pass close to the catcher's initial position would yield later movement initiation than balls projected farther away. This is not what we saw. Most probably, participants simply stepped forward when they saw the ball approach. They knew that all balls would pass in front of their original position, so stepping forward was the logical thing to do. This tendency to step forward, especially on the part of novices, has been seen before (Oudejans et al., 1997). The potential problem is that if one steps forward too far, inertia may prevent a timely return. Indeed, in line with what some participants reported, one of the things they learned with practice was to wait before initiating their movement. Another risk of stepping too far forward was, again, the ball projection's disappearance from the front screen for balls that were going to pass behind the catcher's current position. When that happened, the perception-action cycle was broken, and no successful interception could be made anymore.

General Discussion

We used virtual reality as a tool to study perception-action. More specifically, we studied the judging and intercepting of virtual balls in a CAVE. The rationale for using virtual reality instead of the natural world is the ease of experimentation, but most of all, it is the possibility of manipulating ball trajectories and the relations between ball flight and its optical consequences in a way that would not be possible in reality. We argue that virtual reality holds great promise for unraveling issues woven together by the physics of motion and optics. Using virtual reality for perception-action research, however, also holds a risk. Things are different in virtual reality, and we must be confident that these differences do not preclude generalization to natural perception-action. Thus, the first point on our research agenda was to validate the use of the CAVE for the study of catching fly balls. The present findings should be seen as a first step in that direction.

Participants in our study performed two tasks. In a judgment task, they reported whether virtual balls that approached them would pass behind or in front of them. The results showed that they were able to perform this task successfully. The two major findings were the following. First, we found a relation between the observers' response times and the times to reach threshold values of two particular optical variables. Second, feedback and an intact perception-action coupling played a significant role in the success rate of the judgments. Information on the correct choice after each trial made it possible for observers to deliver almost flawless judgments. Furthermore, in the situation in which ball projections disappeared toward the end of a trial, success rates went down.

We also asked participants to intercept the virtual balls. In the first experiment, the virtual balls had to be intercepted with a hand-held device. Participants were not successful. In the third experiment, we asked the participants to intercept the virtual balls with their foreheads, a task at which they were much more successful. We believe that the critical difference between the two tasks was the feedback that was available in head interception but not in hand interception. There was no haptic feedback, as in normal catching; instead, the presence or absence of explosive optical expansion informed of the relative success of interception. Thus, in both the judging task and the interception task, feedback was essential for successful behavior.

The first aim of the studies presented here was to replicate earlier findings, but now in the CAVE. Before starting to use the CAVE as a tool to study perception and action, it is important to demonstrate that catching fly balls in the CAVE resembles catching under natural conditions. A proper replication would provide the confidence in the possible generalization of results from CAVE research. To what extent did we succeed in this task? First, participants were able to judge the side at which fly balls would pass them. Given that observers were able to make judgments of simulated fly balls on small computer screens (Babler & Dannemiller, 1993; Michaels & Oudejans, 1992; Todd, 1981), sometimes even with balls simulated as 1-pixel-sized dots, it may not come as a surprise that observers in the present studies were able to judge analogous events on a big screen. Surprising or not, the results can be seen as a replication of earlier work. Moreover, the analyses that we presented strongly suggest that the nonuniformity of optic speed is the critical variable for deciding on the passing side of the balls, thus extending previous work.

Second, participants were also able to intercept fly balls, albeit in a somewhat different way than has been studied before. The results from the interception task also replicated earlier work in another important way. Head movements turned out to be consistent with the Chapman Strategy (cf. McLeod & Dienes, 1993, 1996; Michaels & Oudejans, 1992). Optical speed was held constant during successful as well as unsuccessful interceptions. Finally, participants visually tracked the ball they intended to catch. This finding is in line with the results reported by Oudejans et al. (1999) who studied, as we did, the catching of luminous balls in the dark. Thus, it seems fair to conclude that people can perform the tasks of judging and intercepting fly balls in a CAVE and that the way they intercept those balls resembles the way they would do so under natural conditions.

Our endorsement of the CAVE for research on ball catching, in particular, must be tempered, first, by a recognition of the small space, which permits only a few steps at most. As such it is not ideal for testing a strategy for locomotion in catching. Second, we would be remiss if we underestimated the effort expended in tracking down CAVE artifacts—what are the consequences of no ceiling projection, movement-optics lags, and the absence of feedback? It is easy for catching in a CAVE to elbow out catching itself as the topic of scientific inquiry.

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