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Determining whether a ball will land behind or in front of you: Not just a combination of expansion and angular velocity

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Abstract

We propose and evaluate a source of information that ball catchers may use to determine whether a ball will land behind or in front of them. It combines estimates for the ball's horizontal and vertical speed. These estimates are based, respectively, on the rate of angular expansion and vertical velocity. Our variable could account for ball catchers' data of Oudejans et al. [The effects of baseball experience on movement initiation in catching fly balls. *Journal of Sports Sciences, 15*, 587–595], but those data could also be explained by the use of angular expansion alone. We therefore conducted additional experiments in which we asked subjects where simulated balls would land under conditions in which both angular expansion and vertical velocity must be combined for obtaining a correct response. Subjects made systematic errors. We found evidence for the use of angular velocity but hardly any indication for the use of angular expansion. Thus, if catchers use a strategy that involves combining vertical and horizontal estimates of the ball's speed, they do not obtain their estimates of the horizontal component from the rate of expansion alone.

Keywords: Angular expansion; Angular velocity; Optical acceleration; Interception strategy; Fly balls

1. Introduction

Catchers start running in the correct (forward or backward) direction for catching fly balls approximately 500 ms after the start of the balls' flight (McLeod & Dienes, 1993, 1996; Michaels & Oudejans, 1992; Oudejans, Michaels, & Bakker, 1997; Oudejans, Michaels, Bakker, & Davids, 1999). The short reaction time shows that there has to be some visual information that indicates very early during the ball's flight whether the ball will land ahead or behind the catcher. What is this visual information?

1.1. Chapman strategy

Chapman (1968) argued that catchers use the fact that the projection of a ball on a parabolic path decelerates if the ball will land in front of the observation point and accelerates if it is destined to land behind it (see Fig. 1). In principle (but see Rozendaal & van Soest, 2003), all that one has to do to start moving in the right direction is to move forward if the projection decelerates and backward if it accelerates. The catcher could arrive at the landing position of the ball by adjusting his or her running speed in such a way that the projection of the ball keeps moving at a constant speed.[1]

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[1] The speed of the ball's projection is not quite the same as the angular speed. It is the speed of the ball as projected on a static vertical surface. Thus, it will not precisely hold for the projection on a curved, moving retina.

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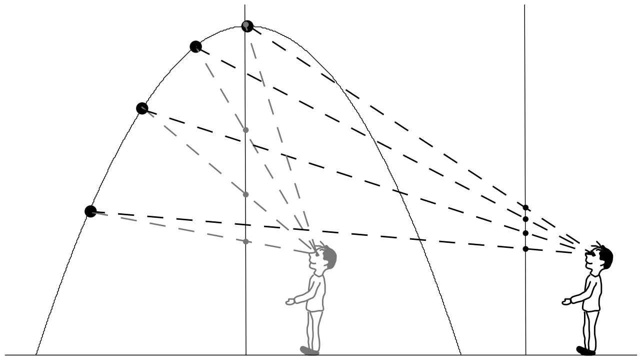

Fig. 1. Schematic illustration of the acceleration cue for determining the running direction to catch fly balls. Four positions of a ball following a parabolic path are indicated at equidistant time intervals. If the ball is destined to land in front of the observation point, its projection decelerates in the vertical direction (depicted as a decreasing distance between the black dots on the vertical line). If the ball will land behind the initial observation point, the ball's projection accelerates (increasing distance between the gray dots on the vertical line).

Some studies suggest that this strategy is indeed used (Babler & Dannemiller, 1993; Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999; McLeod & Dienes, 1993, 1996; McLeod, Reed, & Dienes, 2001, 2003; Michaels & Oudejans, 1992; Zaal & Michaels, 2003), mainly by showing that the running behavior of catchers is consistent with maintaining the speed of the ball's projection approximately constant. Other authors claim that it is not used (Brouwer, Brenner, & Smeets, 2002; McBeath, Shaffer, & Kaiser, 1995; Todd, 1981). Their main argument is that humans cannot detect acceleration sufficiently well. Brouwer et al. (2002) measured the threshold for distinguishing acceleration from deceleration for short presentation times. This threshold appeared to be best expressed as a proportion of velocity change. Brouwer et al. (2002) used raw data from a ball-catching study by Oudejans et al. (1997) to see whether experienced catchers started running after the threshold for acceleration detection was reached. For every trial, the time that the catcher started moving was compared to the time that the change in the velocity of the ball's projection reached the detection threshold. It appeared that in at least half of the cases, catchers started to run in the correct direction before it had been possible for them to detect whether the projection was accelerating or decelerating. Additionally, there was no correlation between the time that the catchers started moving and the time that the detection threshold was reached. Brouwer et al. (2002) concluded that acceleration was not used to determine the initial running direction.

1.2. An alternative cue for determining the initial running direction

Here, we propose an alternative cue that allows catchers to determine whether a ball will land ahead of or behind them. This cue is based on the notion that the combination of the ball's horizontal speed (in the direction towards the observer) and the ball's initial vertical speed (in the upward direction) determines the distance that it is going to cover.[2] We will derive an equation for this distance and present a physiologically plausible way of detecting it.

Ignoring air resistance and assuming that the ball starts moving at eye height, the time T that the ball will remain above eye height is

$$T = \frac{2V_{\mathrm{v}}}{g} \tag{1}$$

with g being the acceleration caused by gravity and V_{v} being the initial vertical speed. The horizontal distance d_f that the ball will cover before passing eye height ('flight distance') is

$$d_f = V_{\mathrm{h}} T \tag{2}$$

with V_{h} being the speed in the horizontal direction. Note that in contrast to the vertical speed, the horizontal speed does not change during the ball's flight. By substituting T from Eq. (1) in Eq. (2), we find that the flight distance of a ball depends on the horizontal and initial vertical speed as follows:

$$d_f = \frac{2V_{\mathrm{h}}V_{\mathrm{v}}}{g}. \tag{3}$$

We denote the distance between the starting position of the ball and the initial position of the catcher as d_{bc}. By expressing the flight distance as a proportion of d_{bc}, we get

$$\frac{d_f}{d_{bc}} = \frac{2V_{\mathrm{h}}V_{\mathrm{v}}}{gd_{bc}}. \tag{4}$$

We call this ratio the 'geometrical predicted distance'. If it is equal to 1, the ball will land (i.e., pass eye height) at the catcher's initial position. If it is larger than 1, the ball will land behind the catcher ($d_f > d_{bc}$). If the geometrical predicted distance is lower than 1, the ball will land in front of the catcher ($d_f < d_{bc}$).

The question arises whether catchers are able to perceive this predicted distance so that they can use it for determining whether they should run backwards or forwards. Catchers probably have implicit knowledge of g through abundant experience with gravity or through the use of graviceptive information (Ando, 2004; Indovina et al., 2005; McIntyre, Zago, Berthoz, & Lacquaniti, 2001), but they do not have direct access to the exact horizontal and initial vertical speed of the ball. They must extract the predicted landing position from correlates of these variables, such as the rate of expansion of the ball's image and its upward angular velocity θ. To obtain an adequate scaling of these variables, one needs a scaling factor such as ball size or the distance at which the ball starts its flight. As

[2] For simplicity we assume that the ball is moving within a vertical plane through the line of sight. In order to catch a real ball people will have to consider its lateral motion as well, but this is presumably relatively simple because whether the ball moves to the left or the right of the observer is directly specified by the angular leftward or rightward motion of the ball's image.

both ball size and starting distance were constant in the experiment of Oudejans et al. (1997), their values could have been judged through experience during the experiment as well as directly on the basis of visual information.

A convenient expression for the estimate of the horizontal speed is d_{bc} divided by an early sample of tau (τ). Tau is the ball's angular size divided by its rate of expansion, and specifies the time to contact for motion at a constant speed (Lee, 1976). A convenient expression for the estimate of the initial vertical speed is d_{bc} times θ (in rad/s). Substituting the ball's horizontal and initial vertical speed in Eq. (4) by these expressions yields a perceptual estimate of the geometrical predicted distance, the 'perceptual predicted distance'

$$ppd = \frac{2d_{bc}\theta}{g\tau}. \tag{5}$$

We estimated the value of *ppd* that the subjects in the study by Oudejans et al. (1997) could have used by averaging the information over the time that the subjects could have seen the ball's motion. As it takes about 110 ms for the arm to respond to a change in visual information (Brenner & Smeets, 1997), and legs have longer neuronal and neuromuscular delays, we used the time between the moment that the ball was fired and 150 ms before the foot's reaction time. We determined this interval separately for each trial. Fig. 2 shows the values of the perceptual variables that contribute to the *ppd* (tau and angular vertical velocity) for every ball shot at experienced catchers in the experiment by Oudejans et al. (1997). White discs represent balls that landed in front of the catcher's initial position and black discs represent balls that landed behind the catcher. As the catchers only started running in the wrong direction in 3% of the trials, the colors can also be read to code whether the catchers expected the ball to land behind or in front of them. The dashed line indicates the combinations of vertical velocity and tau that result in a *ppd* of 1 with lower *ppd*-values above the line and higher *ppd*-values below the line. The white discs are above the line and the black discs are below the line. This means that the approximations of V_h and V_v used in *ppd* are good enough to differentiate between balls landing behind and those landing in front of the catchers. Catchers may therefore have used *ppd* to determine their response.

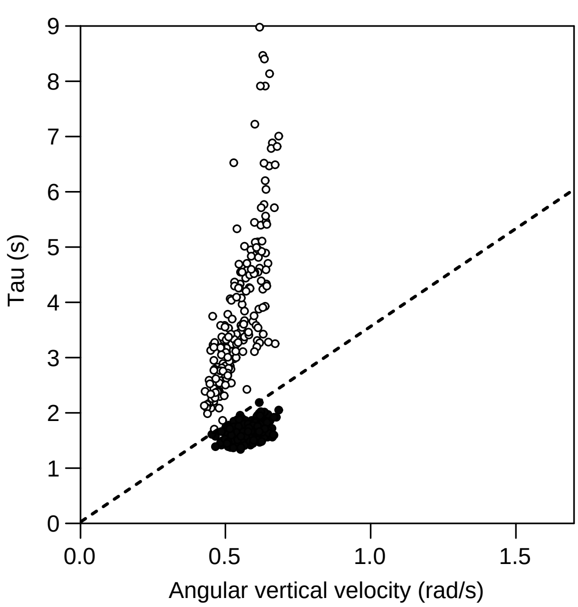

Fig. 2. Average values of angular vertical velocity and tau from the moment the ball appears until 150 ms before the subject starts moving. Each disc represents one ball trajectory in the study by Oudejans et al. (1997, experienced catchers). Balls landing in front of the catcher's initial position are coded in white; balls landing behind the catcher's initial position are coded in black. The dashed line indicates combinations of angular velocity and tau giving a *ppd* of 1. Discs above the line have a lower value of *ppd*; discs below have a larger value. *Ppd* thus correctly separates balls landing behind from ones landing in front of the catcher.

Fig. 2 also shows that the balls' trajectories in the study by Oudejans et al. (1997) were not evenly distributed in terms of angular expansion and angular vertical velocity. This probably arose from the fact that Oudejans et al. (1997) wanted to make sure that their subjects had to run to catch the ball and that they were limited by the ceiling of the hall in which the experiment was carried out. The uneven distribution means that their subjects could have made an almost perfect distinction on the basis of angular expansion alone. In the present study, we test conditions in which subjects must use both components of *ppd* in order to arrive at a correct response. Additionally, we look at the effects of tracking the ball with the head, ball size, monocular or binocular viewing, and manipulated rate of expansion.

2. Methods

We asked our subjects to judge whether simulated fly balls would land in front of them or behind them. Only the initial part of the ball's flight was shown. We chose a set of trajectories for which the use of *ppd* would lead to different responses than either angular vertical velocity or tau alone. Different conditions were examined in four different sessions. In the first session, we presented approaching tennis balls, as in Oudejans et al. (1997). We investigated whether instructing subjects to track the ball with the head or to keep the head stationary makes any difference.[3] One possible concern with these simulations was that the differences in expansion between some balls were close to the spatial resolution of our stimulus: the full range

[3] Zaal and Michaels (2003) and Oudejans et al. (1999) found that ball catchers track flying balls with head movements. They argue that information from the neck muscles and vestibular information may provide more accurate judgments of optical acceleration than retinal motion, which, if subjects use the Chapman strategy, helps the judging of landing locations. We think that even if this information reduces the threshold for distinguishing acceleration from deceleration it is unlikely to influence the initial running direction because such improved information can only be available once the head is following the target adequately, which will take (too much) time.

of differences in the value of tau only corresponded with increases in image size (diameter) between 5 and 16 pixels. In the second session, we therefore increased the ball size to correspond with a volley-ball rather than a tennis ball, which resulted in increases of image size between 16 and 50 pixels. Another concern with the experiment as conducted in the first session was that we allowed subjects to view the display with both eyes, so that information from binocular stereopsis indicates that the balls were not really approaching. Although the resolution for judging distance from binocular cues in such an impoverished visual environment (at that distance) is presumably too low to have influenced subjects' judgments we included a monocular condition in the second session to make sure of this. In the third and fourth sessions, we "artificially" increased or decreased the rates of expansion in order to specifically examine how expansion influences the judgments. In these sessions, the presentations no longer corresponded to rigid balls flying under gravity, so there is no correct answer. However, relying directly on optical acceleration, *ppd*, tau or angular vertical velocity would give predictable responses.

2.1. Materials and stimuli

The setup is depicted schematically in Fig. 3. The subjects sat in a dimly lit room, 5 m away from a screen which was 3 m high and 8 m wide. We simulated white tennis balls (6.6 cm diameter) or white volleyballs (21 cm diameter) on a dark uniform background. The balls started at a simulated and actual distance of 5 m from the observer, 70 cm above the floor (which was approximately at eye height because the subjects sat in a very low chair). After remaining stationary for 200 ms, the simulated balls flew towards the observer following a parabolic path. After the first 319 ms of the flight, the ball disappeared. This was always before the ball's projection would have started to descend or would have reached the upper edge of the screen. Taking the response times in real catching tasks into account, people must usually be able to judge whether a ball will land ahead of or behind them within 319 ms (McLeod & Dienes, 1993, 1996; Michaels & Oudejans, 1992; Oudejans et al., 1997, 1999). Air resistance was ignored in the simulation. This is not expected to result in important errors (Rozendaal & van Soest, 2003). We used a CRT Marque 2000 projector. The resolution was 1280×1024 pixels for an image size of 3.75×3 m, and the frame rate was 72 Hz. The subjects viewed the stimuli with both eyes except for during a certain amount of trials in the second session, when they wore a patch over one eye.

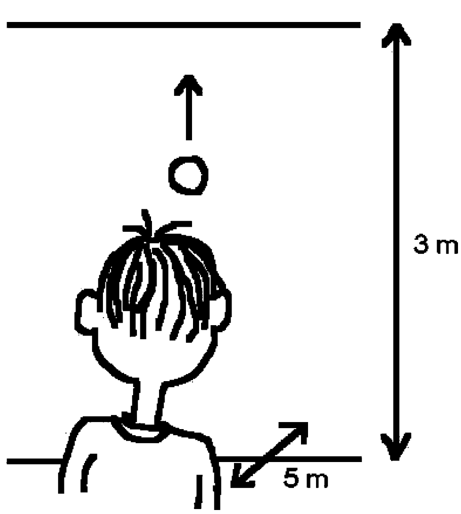

Fig. 3. Schematic illustration of the setup.

The simulated balls could have one out of six different horizontal speeds (4.00, 4.43, 4.90, 5.42, 6.00, and 6.64 m/s) and one out of six different initial vertical speeds (3.45, 3.94, 4.50, 5.13, 5.85, and 6.69 m/s). The values are such that half of the resulting 36 trajectories are simulated to land behind the observer (values over 5 m), and the other half to land in front of the observer (values less than 5 m). The balls' simulated covered distances were between 2.81 and 9.06 m.

2.2. The sessions

Each session consisted of two or three blocks of trials. Each block consisted of 180 trials (5 repetitions of 36 simulated ball trajectories) that were presented in a random order.

In the first session, every subject received two blocks of trials with simulated approaching tennis balls. Viewing was binocular. In one block, the subjects were asked to track the ball with their head. In the other block, they were asked to keep their head stationary. Half of the subjects performed the tracking condition first; the other half performed the condition with the stationary head first. The experimenter stayed in the room to check whether the subjects followed the head movement instructions.

In the second session, every subject received two blocks of trials with simulated approaching volley balls. In one block, viewing was binocular and in the other it was monocular. Half of the subjects performed the binocular condition first; the other half performed the monocular condition first. Subjects received no instructions about head movement.

In the third session, every subject received three blocks of trials. In one block, they were presented with simulated approaching tennis balls as in the first session (except for the absence of any instructions about head movements). In the other two blocks, the rate of expansion was increased or decreased by multiplying or dividing the normal rate of expansion by 1.5. The initial target size corresponded with a tennis ball at 5 m. In this session, the trials of the three blocks were all put together and presented in a completely random order. Viewing was binocular.

The fourth session was identical to the third, except that the rate of expansion was divided or multiplied by a factor 5 rather than by a factor 1.5.

2.3. Subjects

Twelve subjects participated in each session. One of them was one of the authors, who participated in all four sessions. The others were 44 colleagues from the MPI in Tübingen and paid subjects. They were all naïve as to the purpose of the study and participated in one session only.

2.4. Procedure

We told the subjects that we were showing them balls, flying towards them, which would disappear. The subjects were asked to indicate whether the ball would have landed ahead of or behind them by pressing the appropriate button on a keyboard that they had on their lap.

2.5. Training

Before the experimental blocks started, the subjects worked through 324 training trials (9 repetitions of 36 simulated ball trajectories, in random order) during which feedback was provided. The feedback consisted of a large red square that appeared whenever the response was incorrect. The training was intended to encourage people to use information that correctly specifies the balls' landing positions even in this slightly unnatural task of pressing buttons in response to approaching balls. It should also help sub-

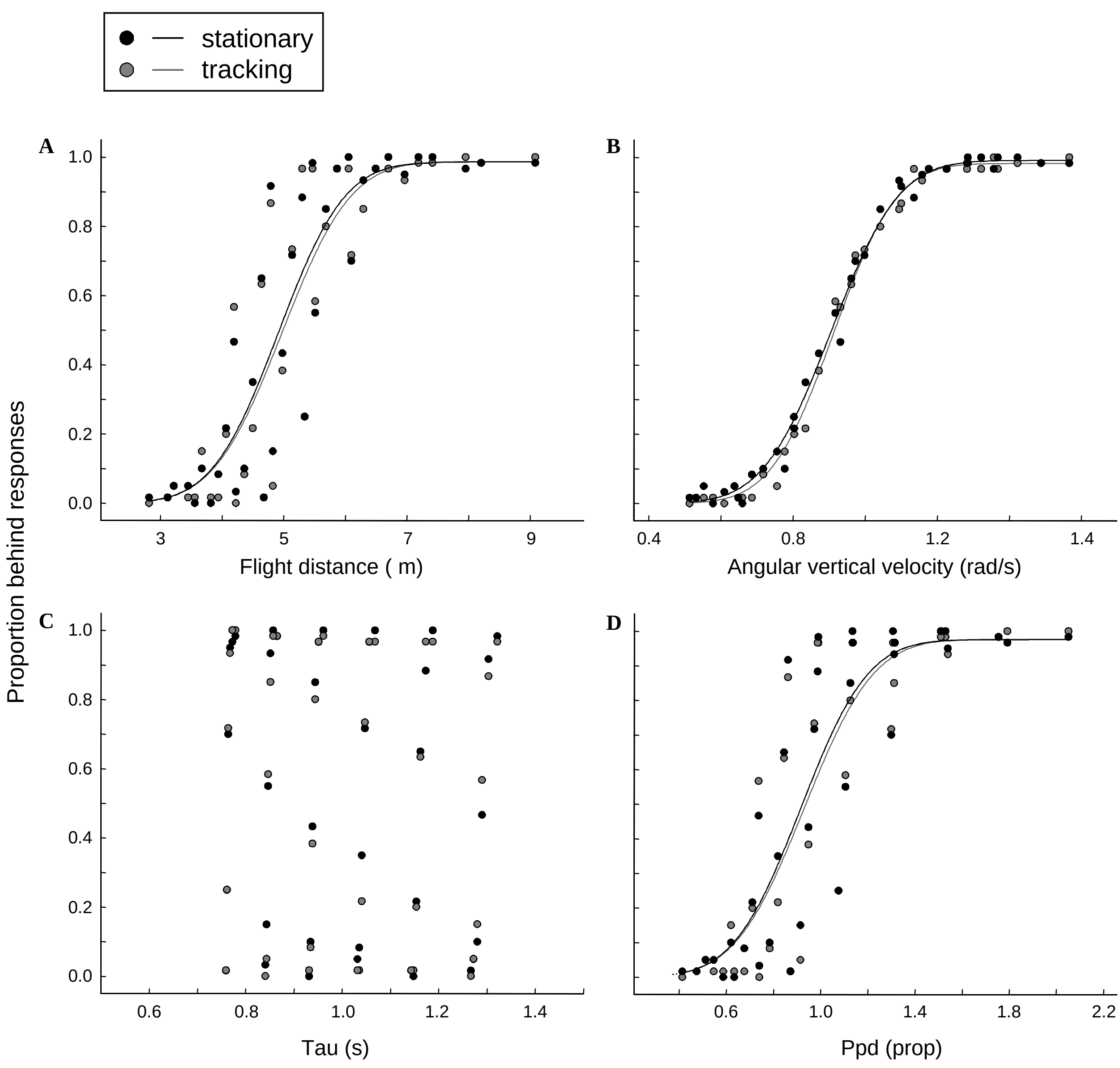

Fig. 4. Proportion of behind responses for each ball trajectory in the first session, as a function of simulated flight distance (A), angular vertical velocity (B), tau (C), and *ppd* (D). The curves are the fitted cumulative Gaussians. The values for angular vertical velocity, tau, and *ppd* are averaged over the 319 ms presentation time. The black dots and curves are for the static head condition. The grey dots and curves are for the head tracking condition. There are no curves in (C) because it made no sense to fit a cumulative Gaussian to these data.

jects to correctly estimate any environmental parameter, such as the initial distance to the ball or ball size, and reduce the variability between subjects. There was no feedback during the actual experiment.

For the subjects in the first session, who first performed the experimental block in which the ball was tracked, half trained with tracking whereas the other half trained with their head stationary. Similarly, for the subjects who first performed the experimental block with the stationary head, half kept their head stationary during training whereas the other half tracked the ball.

For the second session, we used a similar training protocol as for the first session (with binocular and monocular conditions instead of tracking and stationary conditions).

For the third and fourth sessions, we only trained our subjects with balls with a normal rate of expansion (the same block of practice trials as in the first session but without instructions about head movement) because there is no real 'correct' answer for the trials in which the expansion was manipulated.

2.6. Analysis

For each ball trajectory, we determined the average values of angular vertical velocity and tau over the presentation time of 319 ms, and computed *ppd* with these values. We plotted the average proportion of behind responses for each simulated ball trajectory as a function of simulated flight distance (as specified by optical acceleration), angular vertical velocity, tau and *ppd.* We fitted cumulative Gaussians through these points using the least-squares Gauss–Newton method. This was done for each condition separately: two head movement conditions in the first session, monocular or binocular viewing in the second session,

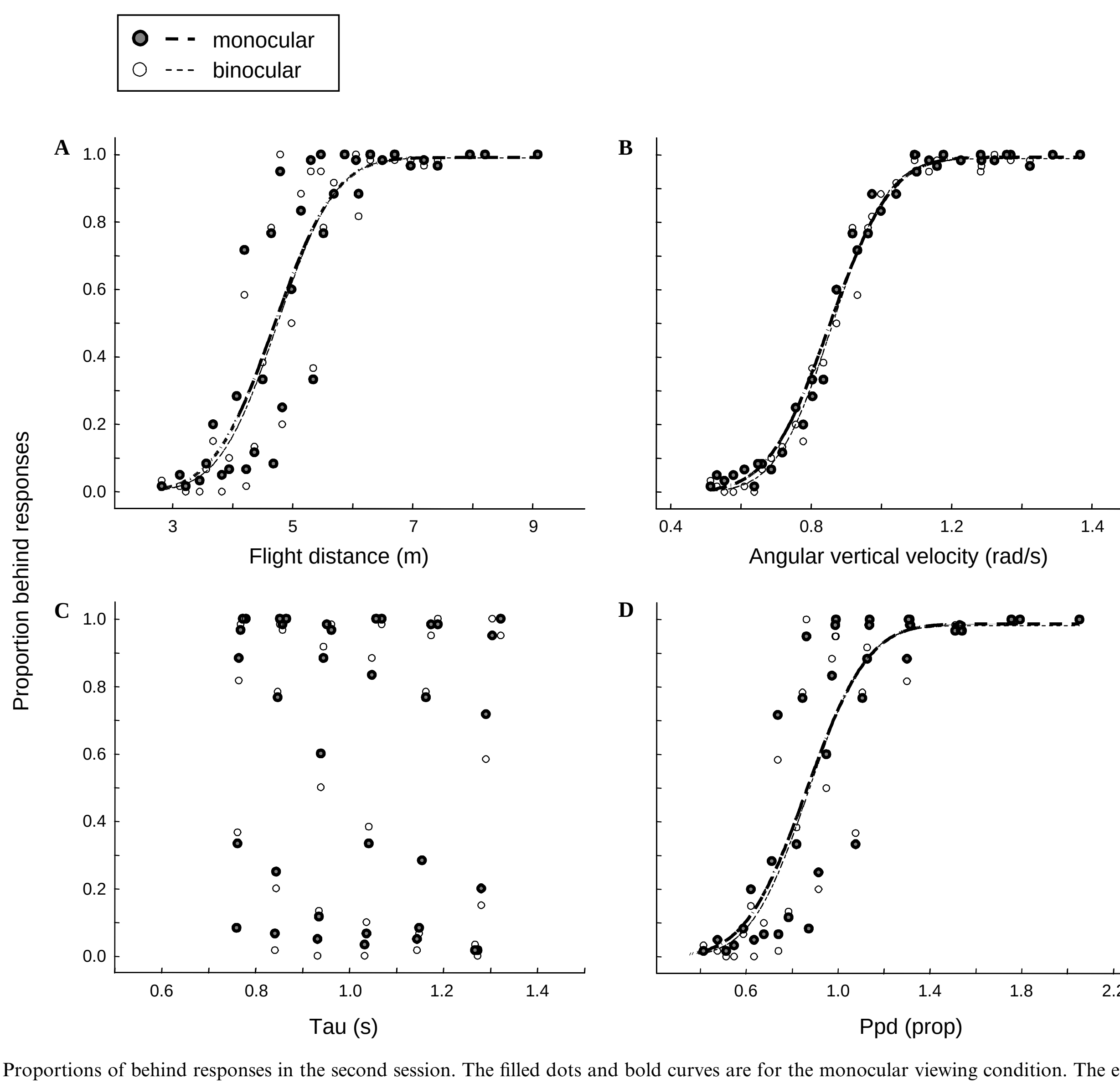

Fig. 5. Proportions of behind responses in the second session. The filled dots and bold curves are for the monocular viewing condition. The empty dots and thin curves are for the binocular viewing condition. Other details as in Fig. 4.

and normal, increased or decreased rates of expansion in the third and fourth sessions. If subjects use a certain variable, we expect to find a neat dependency (good fit) of the proportion of behind responses as a function of the different values of that variable.

To determine whether differences between sessions and conditions are likely to be coincidental, we estimated the 95% confidence intervals of the means and the standard deviations of the cumulative Gaussians fitted through the proportion of behind responses as a function of the best predictor of proportion of behind responses. For this, we used the bootstrap method as implemented by ‘psignifit’, based on 1999 simulations (Wichmann & Hill, 2001).

3. Results

Figs. 4–7 show the average proportion of behind responses for each simulated ball trajectory as a function of flight distance (or optical acceleration) (A), angular vertical velocity (B), tau (C), and *ppd* (D) for the first to the fourth session. The results were very similar for the four sessions. In all cases, the best fit is found for the angular vertical velocity (B): the scatter of the data points around the fitted cumulative Gaussians was clearly larger for proportion of behind responses as a function of flight distance (A) or *ppd* (D) than for plots as a function of angular vertical velocity alone. For tau (C), the fits are so poor that we

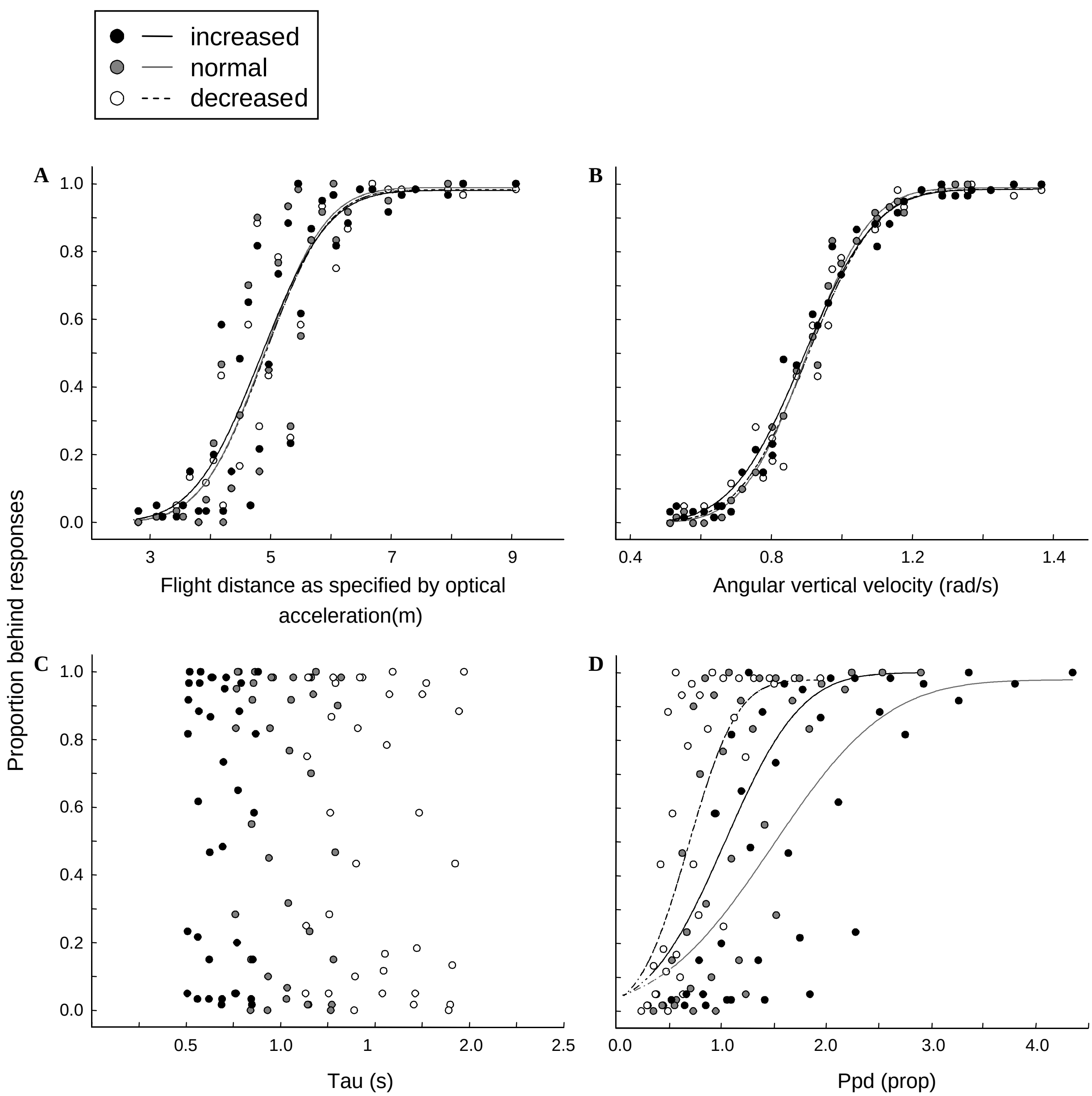

Fig. 6. Proportions of behind responses in the third session. The black dots and curves are for the increased expansion condition. The grey dots and curves are for the normal expansion condition. The empty dots and dashed curves are for the decreased expansion condition. Panel (A) is now labeled ‘Flight distance as specified by optical acceleration’, because the simulated image sizes no longer correspond with the flight of rigid objects under gravity. Other details are as in Fig. 4.

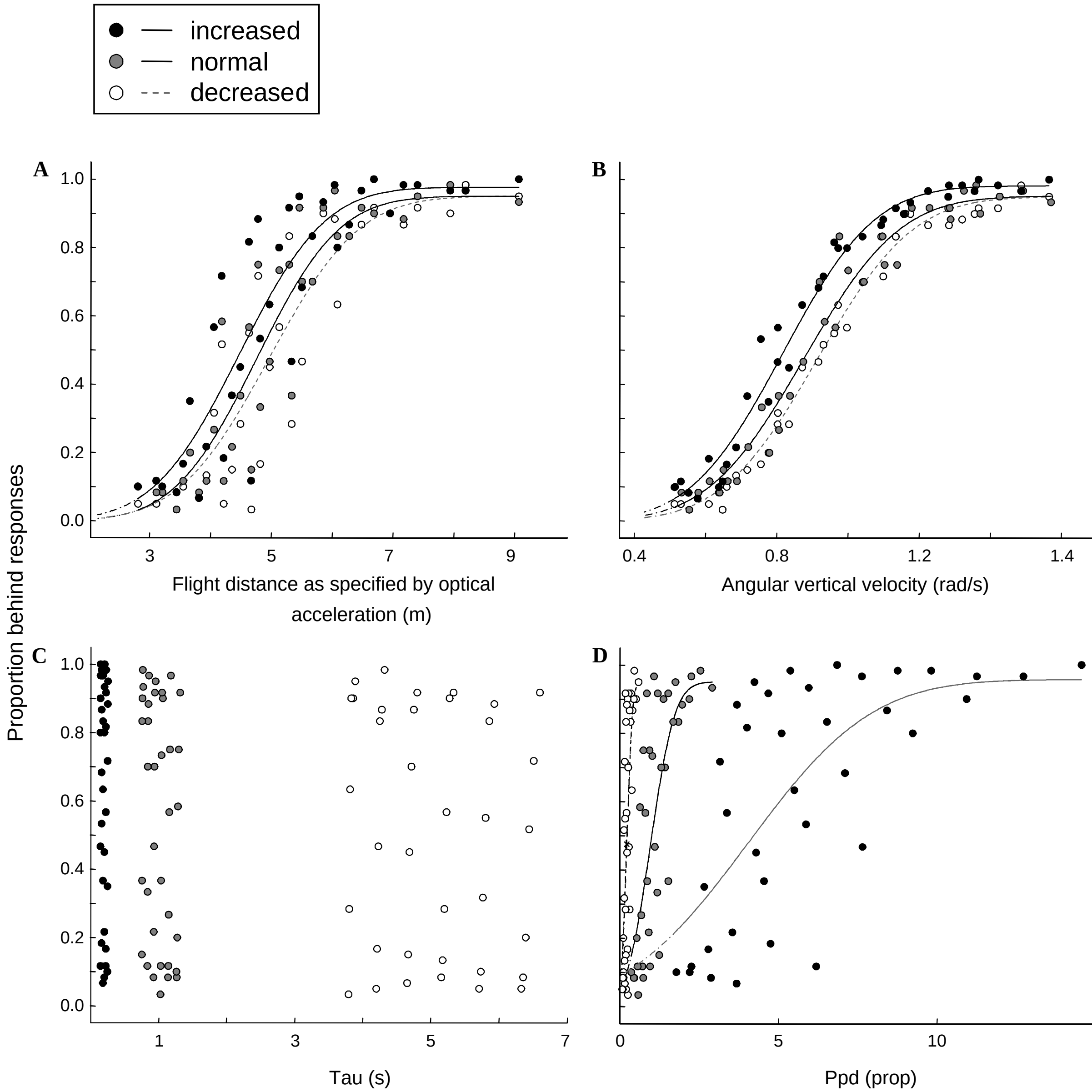

Fig. 7. Proportions of behind responses in the fourth session. For details see legend of Fig. 6.

did not draw the best-fitting curves. Thus, subjects seem to rely exclusively on angular vertical velocity. We plotted the means (Fig. 8A) and the standard deviations (Fig. 8B) of the fitted Gaussians as a function of angular vertical velocity. The error bars indicate their 95% confidence intervals.

Fig. 4 shows the data for the first session, with separate points and fits for the two head movement conditions. There is clearly no difference between the responses when subjects were instructed to track the ball and when they were instructed to keep their head stationary (see also the first two bars and their overlapping confidence intervals in Figs. 8A and B).

Fig. 5 shows the data for the second session, with separate points and fits for monocular and binocular viewing. Again there is no difference between the two conditions, but the point of subjective equality (the average value of the fitted Gaussian) is slightly lower than it was for the first session (compare the third and fourth bars with the first two in Fig. 8A). This larger proportion of behind responses could result from the larger ball size (see Section 4).

Figs. 6 and 7 show the data for the third and fourth sessions, with separate points and fits for presentations with normal, increased, and decreased rates of expansion. For a modest manipulation of the rate of expansion (Fig. 6), the fits for the three conditions were almost identical when expressed as a function of the angular vertical velocity. They were also very similar to the fits for the first session (see Fig. 8). For a large manipulation of the rate of expansion (Fig. 7), the conditions affect the horizontal position of the curves fitted as a function of angular vertical velocity (i.e., the average values of the fitted Gaussians are different; see also Fig. 8A). Also, the slopes in the fourth session are

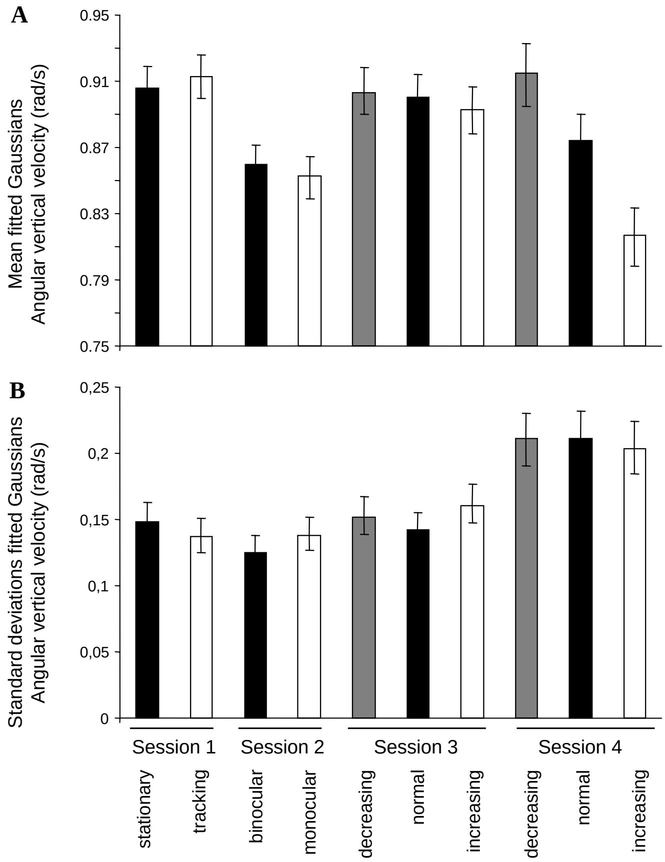

Fig. 8. Means (A) and standard deviations (B) of the fitted cumulative Gaussians for the proportions of behind responses as a function of vertical angular velocity. Each bar represents one condition within one session. The error bars indicate the 95% confidence intervals that were determined with the bootstrap method.

shallower than in the other sessions (i.e., the standard deviations of the fitted Gaussians are larger; see also Fig. 8B).

4. Discussion

In all four sessions, our subjects seemed to base their judgments of whether a ball will land behind or in front of them on vertical angular velocity alone. Only the effect of the conditions on the means of the fitted Gaussians in session 4 (Fig. 7B) could be the result of a small contribution of retinal expansion or tau on the judged landing position as predicted (though to a much stronger extent) by *ppd*. However, it could also be the result of the difference in (average or final) ball size between the conditions. A tendency of subjects to respond more behind for larger average ball sizes would explain the observed effect of expansion condition on the mean of the fitted Gaussians because for the increased expansion condition the average ball size is large, and for the decreased expansion condition the average ball size is small. This interpretation is supported by the fact that there is still no effect of tau on the proportion of behind responses in the fourth session (Fig. 7C) and the finding that we also found a low mean of the fitted Gaussians in the second session in which a large ball was presented. In addition, responding behind more often for larger balls is in line with the finding that the judged time to contact with a simulated approaching ball is earlier for larger ball sizes (Van der Kamp, Savelsbergh, & Smeets, 1997; Wann, Field, Mon-Williams, & Milner, 2005): a shorter estimated time to contact could lead to a higher estimated horizontal velocity and consequently to more behind responses. The relatively large variability in average size of the ball's image in the fourth session may have caused a general decrease in performance (i.e., the shallow slopes). We conclude that our subjects did not use rate of expansion in initially judging a ball's landing location. Of course, this does not mean that the rate of expansion is not used in other aspects of a ball-catching task such as determining the timing of the grasp in the final stage of catching a ball (Rushton & Wann, 1999; Savelsbergh, Whiting, & Bootsma, 1991).

In the second session, we found that wearing a patch over one eye does not affect the balls' apparent landing position. This is consistent with binocular information not being very effective at a distance of 5 m and not even always having much influence on performance in related tasks at smaller distances (Gray & Regan, 1998; Harris & Drga, 2005; Rushton & Wann, 1999; Savelsbergh et al., 1991).

We did not find evidence for a better performance when subjects were tracking the ball with their head than when they were holding the head stationary, which was argued to possibly improve performance by reducing the threshold for distinguishing acceleration from deceleration (Zaal & Michaels, 2003). Our results are consistent with the argument that optical acceleration is not likely to be used in judging where a ball will land because this would have resulted in a nice dependency of proportion behind responses on flight distance. Probably, people cannot distinguish between acceleration and deceleration well enough in order to use this information (Brouwer et al., 2002; McBeath et al., 1995; Todd, 1981).

In the introduction we showed that the use of *ppd*, which involves tau (rate of expansion) as well as angular vertical velocity, could account for the performance in an experiment by Oudejans et al. (1997). In that experiment, subjects could have performed correctly on the basis of *ppd*, tau alone, or optical acceleration, but not on the basis of vertical velocity. In the present study, we found the opposite result: subjects only relied on the vertical angular velocity. We can therefore conclude that the information that people use depends on the circumstances. Perhaps the resolution with which people can judge the rate of expansion or can judge the difference in velocity between the images in the two eyes is simply too low when the balls are presented on a uniform background, as they were in our simulations. Normally, subjects will be able to relate the ball's angular size to other objects in the surrounding and to extract binocular information about the ball's motion from changes in disparity relative to surrounding static structures. The only source of information about horizontal velocity that was present in our study was the rate of expansion. Our subjects' poor performance (in terms of complying with the flight distance in the first two sessions) suggests that some critical information is missing in our simulations. We do not think that the fact that our subjects were not ball-catching experts is very important, because Oudejans et al. (1997) showed that when subjects judge whether real balls are going to land behind or in front of them, there was no effect of expertise at all. Both experienced and non-experienced catchers made very few errors. Whether our subjects relied almost exclusively on the angular vertical velocity because this was the only information in our display that they could make sense of, or whether this is normally also an important source of information, and the accompanying source of information about horizontal motion was simply missing, remains to be seen.

Acknowledgments

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