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Peper, C.E.; Bootsma, R.J.; Mestre, D.R.; Bakker, F.C.

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Catching Balls: How to Get the Hand to the Right Place at the Right Time

Lieke Peper, Reinoud J. Bootsma, Daniel R. Mestre, and Frank C. Bakker

Information specifying the future passing distance of an approaching object is available (in units of object size) in the ratio of optical displacement velocity and optical expansion velocity. Despite empirical support for the assumption that object size can serve as a metric in the perception of passing distance, the present series of experiments reveals that in catching a ball subjects do not rely on such "point-predictive" information. The angle at which (real and simulated) balls approached the subject systematically affected verbal and manual estimates of future passing distance, as well as the kinematic characteristics of catching movements. To catch a ball, the actor uses momentary action-related information instead of spatiotemporal estimates. The hand velocity is geared to information specifying the currently required velocity. This secures ending up at the right place in the right time, regardless of where this may be.

To be successful in interceptive actions, like catching or hitting a ball, the movement behavior of the actor has to be very precisely attuned to the spatiotemporal characteristics of the event. The timing of interceptive acts is generally considered to be based on visual information about the time remaining until the object reaches the observer. In line with Gibson's (1966, 1979) notion of optical specification of information, Lee (1976) derived an optical quantity that specifies this "time-to-contact" (t_c), namely, the inverse of the relative rate of dilation of the ball's optical contour that is generated in the optic array by the relative approach between ball and point of observation. This optical quantity, termed τ (tau), specifies the time remaining until the ball makes contact with the point of observation if velocity of approach remains constant. Because accelerative forces are neglected in this time relationship, Lee and Young (1985) proposed to denote the physical quantity specified by the optical variable τ as the τ-margin (i.e., distance remaining divided by velocity of approach). The τ-margin, of course, equals the time-to-contact if no accelerative forces are acting on the ball. Several studies indicate the use of τ in the guidance of spatiotemporal acts (e.g., Bootsma & Van Wieringen, 1988, 1990; Lee, 1976, 1980; Lee, Lishman, & Thomson, 1982; Lee & Reddish, 1981; Lee, Young, Reddish, Lough, & Clayton, 1983; Savelsbergh, Whiting, & Bootsma, 1991; Stoffregen & Riccio, 1990; Wagner, 1982; Warren, Young, & Lee, 1986). Moreover, in a study of visual timing in hitting an accelerating ball, Lee et al. (1983) provided evidence for the argument that even in this case the action was geared to the information about the τ-margin (visually accessible through τ), rather than to information about "real" time-to-contact.

To catch a ball, the hand has to move in such a way that it arrives at the right place at the right time. In most cases, the flight trajectories involved will not bring the ball directly to the point of observation. Balls that will eventually pass the observer on either side may be caught by moving the hand in a sideward direction. Predictive information regarding when and where the ball can be intercepted would allow prospective coordination of the action (Bootsma & Peper, 1992). With respect to the temporal aspect of such an action, elaborations on τ have demonstrated that optical specification of the time remaining until a ball reaches any specified point is in fact available (Bootsma, 1988; Bootsma & Oudejans, 1993; Tresilian, 1990). When the distance between the object and the eye remains constant (i.e., if the optical image size is not changing), time-to-contact is specified by the relative rate of constriction of the optical gap between the object and the target position. Empirical results indicate that in judging time-to-contact between two objects moving parallel to an observer's fronto-parallel plane, this optical variable is used indeed (Bootsma & Oudejans,

Lieke Peper and Frank C. Bakker, Faculty of Human Movement Sciences, Free University, Amsterdam, The Netherlands; Reinoud J. Bootsma, Faculty of Sport Sciences, University of Aix-Marseille II, Marseille, France; Daniel R. Mestre, Cognition & Movement, National Scientific Research Center, and Faculty of Medicine, University of Aix-Marseille II, Marseille, France.

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Correspondence concerning this article should be addressed to Lieke Peper, Faculteit der Bewegingswetenschappen, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands. Electronic mail may be sent to L__Peper@sara.nl.

1993).[1] However, interceptive actions generally deal with approaches involving expansion of the object's optical contour. In such situations, time-to-contact is not specified by the rate of constriction of the optical gap, and time-to-contact judgments are not based on this information quantity (Bootsma & Oudejans, 1993; Tresilian, 1994). In line with Bootsma's (1988) analytical derivation, recent empirical findings suggest that temporal information is obtained through a combination of the relative rate of constriction of the optical gap and the relative rate of dilation of the object's image (Bootsma & Oudejans, 1993).

We conclude that the proper timing of the hand movement in catching a ball can be achieved by relying on perceptual information specifying the time remaining. In addition to this source of temporal information, the actor needs predictive spatial information. To catch a ball that will pass at some sideward distance, the observer might use information specifying this future passing distance. To date, however, few authors have addressed the predictive spatial aspect involved (i.e., the prediction of the position at which the ball can be intercepted).

The few existing studies on predictive spatial information have been mainly concerned with the specification of direction of motion. Schiff (1965) demonstrated that fiddler crabs, presented with asymmetrically expanding shadow patterns, tended to move at approximately right angles to the apparent path of approach, and he suggested that the animals may pick up information concerning the path of approach as specified by the degree of skew in the optical magnification pattern. Lee and Young (1985) pointed out that the displacement of the center of expansion that occurs when an approaching object will not make contact with the point of observation can be used to obtain the direction of motion. Fitch and Turvey (1978) formulated the same concept, but from the perspective of occlusion of background. Regan (1986) demonstrated that direction of motion is specified monocularly by the relation between the velocities of the object's edges. Binocularly, the direction in which an object is moving can also be perceived on the basis of the ratio between the velocities of the object's left and right retinal image (Regan, Beverley, & Cynader, 1979). However, it is important to realize that direction of motion itself is not enough to allow prediction of future passing distance, as the latter requires direction of motion to be combined with knowledge of the current distance.

Todd (1981) demonstrated the availability of visual information specifying whether a ball on a parabolic flight trajectory will eventually land behind or in front of the point of observation. Although this information does not provide a useful metric for perception of the future landing distance relative to the current position of the observer, it does specify the direction of movement (forward–backward) required for contact between the ball and the point of observation to occur. This type of action coordination is closely related to the strategy proposed by Chapman (1968): Moving (forward–backward; left–right) in such a way that the optical displacement velocity of the ball remains constant will eventually result in a collision between the ball and the point of observation. In other words, by keeping the optical velocity of the ball constant, the catcher will end up in the correct position to catch the ball. Recently, empirical support for this type of coordination was reported by Babler and Dannemiller (1993) and Michaels and Oudejans (1992). Michaels and Oudejans showed that their subjects (softball players) stuck to such a strategy until just before contact. During the last 300 ms before the ball was caught, this strategy was abandoned. In this way, a collision with the head was avoided and the ball was caught at some distance from the point of observation. This implies that in addition to information guiding the catcher's gross movement in the field, information subserving the hand positioning is required.

In the present study, we investigated the source(s) of information used in catching an approaching ball that will eventually pass at a relatively small sideward distance. One possible way is to coordinate the action on the basis of predictive information about the moment and the distance at which the ball will break the fronto-parallel plane of the observer. The perception of the time remaining has already been addressed in the recent elaborations of Lee's τ (Bootsma, 1988; Bootsma & Oudejans, 1993; Tresilian, 1990). In the next section, we derived an optical variable specifying future passing distance. In the experiments to be presented thereafter, we investigated the assumption that predictive information about "when the ball will be where" is used in the coordination of the catching act.

Optical Specification of Passing Distance

Using the same type of analysis as Todd (1981), an optical variable specifying future passing distance can be derived (cf. Bootsma, 1991; Bootsma & Peper, 1992). For our purposes we chose to denote physical size and distances by uppercase letters, whereas the corresponding lowercase letters indicate optical variables. The dot notation is used to indicate the time derivatives: Velocity is denoted by a single dot, acceleration by two dots. Because optical variables associated with one surface can be uniquely transformed into optical variables associated with any other surface (Lee, 1974; Todd, 1981), the present analysis is performed in reference to a planar surface parallel to the approaching object at unit distance from the point of observation, for reasons of mathematical convenience (Figure 1).

The movement of an approaching object in the X–Z plane is completely described as follows:

[1] In a similar vein, Kaiser and Mowafy (1993) demonstrated that in the absence of dilation of the object's optical contour the time remaining until an approaching object breaks the observer's fronto-parallel plane is judged on the basis of the relative rate of expansion of the optical gap between the line of sight and the approaching object (global τ; cf. Tresilian, 1991). Global τ provides a rich source of information in situations in which expansion of the object's optical contour may not become salient until the object is temporally proximal, for example in navigation through the environment (Kaiser & Mowafy, 1993).

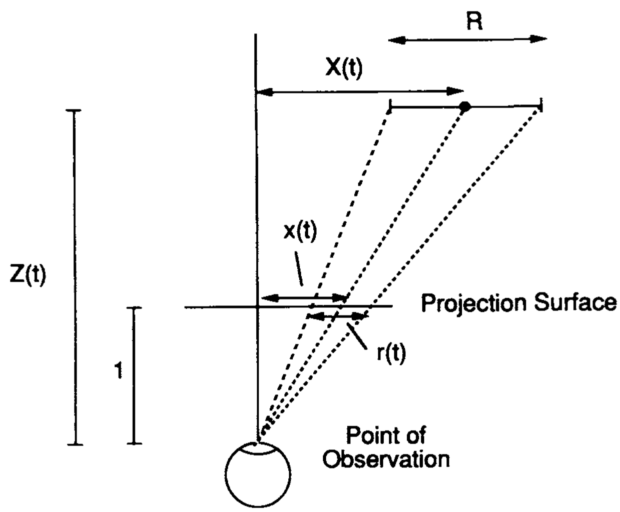

Figure 1. Geometrical relations between a moving object and a projection plane. The object with size R at current distance $Z(t)$ and sideward distance $X(t)$ is specified by optical sideward distance $x(t)$ and optical size $r(t)$.

$$Z = \frac{R}{r}, \quad (1)$$

$$\dot{Z} = \frac{-R\dot{r}}{r^2}, \quad (2)$$

$$\ddot{Z} = \frac{2R\dot{r}^2}{r^3} - \frac{R\ddot{r}}{r^2}, \quad (3)$$

$$X = Zx, \quad (4)$$

$$\dot{X} = Z\dot{x} + \dot{Z}x, \quad (5)$$

and

$$\ddot{X} = Z\ddot{x} + 2\dot{Z}\dot{x} + \ddot{Z}x. \quad (6)$$

If a ball is thrown toward the observer, it seems reasonable, for a first approximation, to neglect the effects of the air resistance ($\ddot{Z} = 0$). The position (X_c) where the object will break the fronto-parallel plane ($Z = 0$) can be derived from

$$X_c = X - \dot{X}t_c - 0.5\ddot{X}t_c^2. \quad (7)$$

Equation 7 concerns future passing distance in the horizontal (X–Z) plane. Note that this relation can be transformed into the vertical direction (which would be the Y-direction for the reference frame defined in Figure 1, perpendicular to the page plane) by simply substituting Y for X. Accordingly, future passing height (Y_c) could be derived. For our purposes, however, we focus on the horizontal distance.

If no sideward deviation due to spin is to be considered ($\ddot{X} = 0$), Equation 8 can be simplified to

$$X_c = X - \dot{X}t_c. \quad (8)$$

If velocity of approach is constant ($\ddot{Z} = 0$), t_c equals the τ-margin. As discussed in the introduction, interceptive actions seem to be geared to this τ-margin, even when velocity of approach is not constant. The τ-margin is optically specified by the variable τ, the inverse of the relative rate of dilation of the projected image:

$$\tau\text{-margin} = -\frac{Z}{\dot{Z}} = \frac{r}{\dot{r}} = \tau. \quad (9)$$

By substituting Equations 1, 4, 5, and 9 in Equation 8, we obtain,

$$X_c = \frac{\dot{x}}{\dot{r}}R,$$

which can be rewritten as

$$\frac{X_c}{R} = \frac{\dot{x}}{\dot{r}}. \quad (10)$$

Equation 10 shows that the future distance at which a ball, approaching at a constant velocity, will break the fronto-parallel plane is optically specified, in units of ball size, by the ratio of the velocity of the sideward displacement of the center of expansion $\dot{x}$ and the rate of expansion of the object image $\dot{r}$. This dimensionless ratio is to be considered a single informational invariant. It is interesting that the ratio $\dot{x}/\dot{r}$ specifies whether a collision between the object and the point of observation is imminent, whatever the size of the object: If the magnitude of $\dot{x}/\dot{r}$ falls within the critical range of –0.5 to 0.5, a collision will eventually occur, because this implies that the center of the object will pass at a distance that is smaller than half the object's size.

In the analysis, optical ball size is approximated by using planar projection of an approaching flat disk, instead of the visual angle subtended by a spherical ball. This approximation is reasonable for balls passing at relatively small lateral distances and, therefore, is suitable for the purposes of the present study dealing with the information used in catching balls that pass more or less within reach.

The mathematical analysis demonstrates that an optical specification of future passing distance (in units of ball size) is available in principle. In the series of experiments to be reported here, we investigate whether this potential source of information is in fact used by the human actor in catching a ball.

Experiment 1: Ball Size as a Metric

As is evident from Equation 10, the ratio $\dot{x}/\dot{r}$ specifies future passing distance in units of ball size. In other words, if this optical specification is used, future passing distance should be scaled to the size of the approaching ball. In Experiment 1, this hypothesis was tested by introducing unexpected manipulations of ball size. If the subject would (mistakenly) scale passing distance to a standard ball size, unexpected introduction of a larger ball would lead to underestimation of future passing distance, whereas a smaller ball would induce overestimation. Equation 10 allows precise predictions of the magnitudes of these shifts.

We adopted the experimental paradigm for studying the perception of affordances (cf. e.g., Marks, 1987; Warren, 1984; Warren & Whang, 1987). In this way, a critical distance can be derived, beyond which an observer judges the future passing distance of approaching balls to be out of reach (Bootsma, Bakker, Van Snippenberg, & Tdlohreg, 1992). In the present context, this method was used to test the hypothesis that the judged critical passing distance is a function of ball size, provided that the subjects are unaware of the changes in ball size.

Because the optical quantity $\dot{x}/\dot{r}$ is a specification in a single two-dimensional projection plane, it should be perceivable with one eye. For this reason, observers performed the judgment task under monocular conditions. Moreover, in monocular viewing no unambiguous optical information about object size is available (Regan & Beverley, 1979).

Method

Subjects. Eight naive subjects (five men, three women) were tested. Their mean age was 27.1 years (range = 21–31), and their mean maximal sideward reaching distance (defined as half the distance between the left and right finger tips if the arms are maximally spread) was 92.2 cm (*SD* = 3.4 cm). All reported normal or corrected-to-normal vision.

Experimental set-up. The set-up is schematically represented in Figure 2. From a rail attached to the ceiling (6.0 m above the floor) of a large experimentation hall 10 balls were suspended using fishing line (4.95 m long), with adjacent suspension points 10 cm apart. The first ball hung 0.5 m and the last ball 1.4 m to the right of the sagittal midline of the observer. Prior to the start of each block of trials, the balls were pulled up and back to a fixed beam, 3.2 m in length and 5.1 m above the floor. Before release, the balls were held in place by means of 10 solenoids on the fixed beam, separated by 12.5-cm intervals. The solenoids were controlled by an Olivetti M24 microcomputer.

During a block of trials all 10 balls were released one by one in a randomized order. On release, a ball would fall out of the solenoid and swing across the room in one arc, reaching its lowest point of 1 m at a distance of 1.3 m in front of the observer. After passing through the observer's fronto-parallel plane (at a passing height of 1.2 m), the ball would be caught on a 4-m-long rod, positioned 0.7 m behind the observer at a height of 1.7 m. After the observer completed a block of trials (10 balls), the rod could be used to pull the balls back up to the fixed beam. Three types of balls, which differed in diameter, were used: 4.9 cm ("small"), 5.75 cm ("standard"), and 6.9 cm ("large"). All were painted black. Balls of different diameter did not differ with respect to the flight time.

To prevent the subjects from looking up to see the position from which the current ball had been released, they were asked to wear liquid crystal display (LCD) goggles that could be made to change from opaque to transparent and back to opaque, with a rise and decay time of 3–5 ms. To secure optimal synchronization, the moments of opening and closing of the glasses were also controlled by the Olivetti M24. Total flight time of the ball, measured from release until passage of the subject's fronto-parallel plane, was about 1.45 s. During the task, subjects stood on a thin wooden platform. Their feet were strapped to the platform to insure a constant, slightly opened stance.

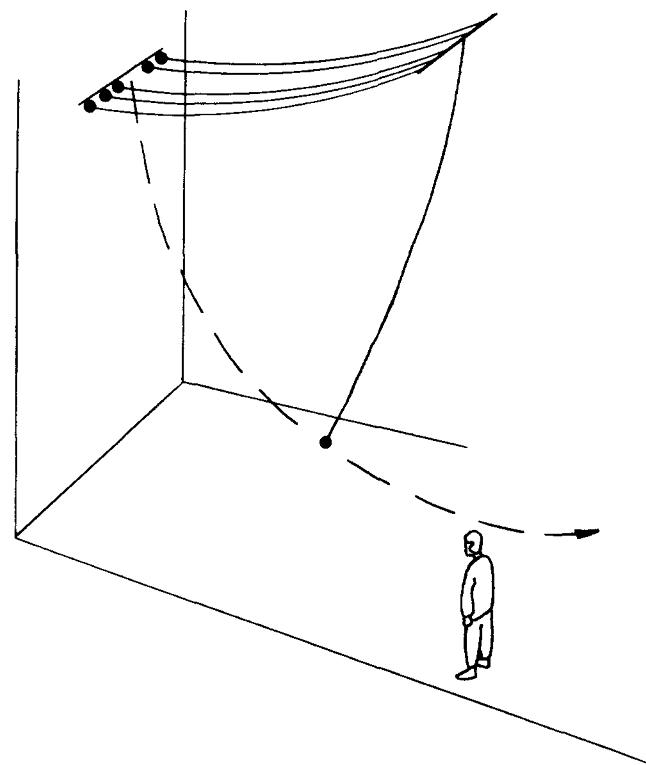

Figure 2. Schematic representation of the experimental set-up. In Experiment 1, 10 balls passed the subject on the right-hand side. (See text for details.)

Procedure. The subject was positioned on the platform and instructed to indicate verbally whether an approaching ball would be reachable simply by stretching the right arm, without sideward leaning to enhance maximal reach. The judgment was not to be accompanied by an actual reaching movement. The subject was told to look straight ahead.

After a ball was released, the glasses remained opaque for 700 ms. Hereafter, one lense (for the dominant eye only) became transparent for 600 ms, after which it changed to opaque again, 150 ms before the ball passed the subject.

During each block of trials, the 10 balls passed the subject on the right-hand side. They were always released in random order. First, two test blocks were presented in which only standard-sized balls (5.75 cm in diameter) passed the subjects. In the following experimental blocks, 1 of the alternative balls was presented along with the remaining 9 standard balls. The position of this odd ball in the first experimental block was inferred from the judgments made during the test blocks. The odd ball's position was changed over the blocks, following the procedure of staircasing (or up-and-down method, Dixon & Massey, 1969). If the subject indicated that the ball was reachable, it would be presented one position further to the right (further away from the subject) in the next block. If it was judged to be out of reach, it would be presented one position closer to the subject. In this way the odd ball's positions concentrated around the critical distance. The total number of experimental trials ranged from 15 to 17, leading to a fixed nominal sample size (15).[2] No feedback on the judgments was provided.

Two-minute-long rest periods were administered between blocks, during which time the balls were pulled up and repositioned. The subject would simply sit down in a chair, still wearing the opaque glasses. Halfway through the session, a short break was given, during which the subject was allowed to take off the goggles.

A session took about 1.5 hr. Because two alternative balls (small and large) were to be considered, each subject was tested in two sessions on different days. The days on which the small or large balls were presented were counterbalanced over the subjects. After the second session had been completed, subjects were asked individually whether they had noticed the differences in ball size. None of them responded positively to this question.

Analysis. To obtain the critical passing distance (or 50% point) at which 50% of the balls were indicated to be no longer reachable, we used two different analyses. The staircasing method was used to find the critical distance indicated for the odd balls (Dixon & Massey, 1969). For each subject the obtained judged critical passing distances were scaled to maximal reach.

The standard balls were judged twice, once during the session with the small ball staircase and once with the large ball staircase. The critical distance for the standard ball was calculated for both sessions separately. As a consequence of the staircase method, the standard-sized ball was judged at some distances in every block, but it was judged a smaller number of times when it appeared near the critical point observed for the staircasing odd ball. In order to keep the number of observations equal over the passing distances, only the first 9 judgments for each distance were considered. For each subject the passing distances were scaled to maximal sideward reach. The percentage of balls judged to be unreachable typically increased over the range of scaled passing distances following an S-shaped curve. Therefore, the critical distance was derived, for each subject, by curve-fitting the reachability scores, as obtained for the range of scaled passing distances, to a logistic (or S-shaped) function of the form

$$y = \frac{100}{1 + e^{-k(c-x)}}, \tag{11}$$

where y is the percentage judged unreachable, 100 is the maximum percentage, x is the scaled passing distance, c is the 50% point, and k is a measure of the slope at this point (Bootsma et al., 1992). The scaled distance at which 50% of the balls were deemed to be no longer reachable, c, was regarded as the scaled judged critical distance.

Results

The observed reachability scores for the standard ball showed a good fit with the logistic function (Equation 11) for all subjects in both sessions (R^2 ranging from .96 to 1.00).[3]

The mean scaled judged critical distances obtained for the four categories (for the small ball, the large ball, and twice for the standard ball) are represented in Figure 3. An analysis of variance (ANOVA) with repeated measures for the factor Ball Size (4), performed on the scaled judged critical distance, revealed that the between-subject variation accounted for 57% and the factor Ball Size for 37% of the total variance. The effect of Ball Size turned out to be significant, $F(3, 21) = 41.5$, $p < .001$). Post hoc Newman-Keuls comparison showed a significant difference ($p < .01$) between all means except between the two mean scaled judged critical distances obtained if the standard ball was presented.

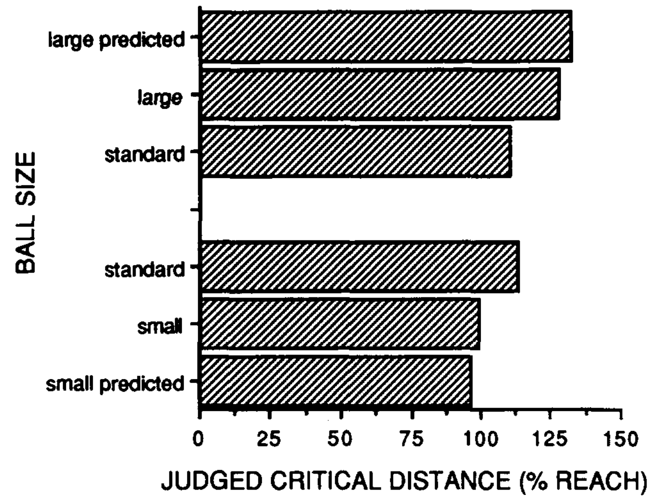

Figure 3. Mean judged critical passing distance, scaled to maximal sideward reach, as a function of ball size (mean SD = 14.0%). The predicted values were calculated on the basis of Equation 10 and the value obtained for the standard ball. (See text for details.)

As is evident from Figure 3, the directions of the shifts in judgment confirmed the hypothesis. Note that overestimation of future passing distance implies that the subject judged balls that were passing within reach to be unreachable. In other words, the judged critical passing distance was smaller if the future passing distance was overestimated and larger if the future passing distance was underestimated.

To further test the assumption that the observed shifts in scaled judged critical distance observed for the odd balls were due to scaling to the standard ball size, we compared the data to specific predictions with respect to the magnitude of these shifts. Multiplication of the individual values obtained for the judged critical distance for the standard ball size with the quotient of odd size and standard size allowed for the predictions of judged critical distances for both odd balls. For the small ball, the magnitude of the shift in judged critical passing distance was predicted to be 16.8% of mean maximal sideward reach. The observed shift turned out to be a little smaller on average (13.7%). However, the difference between the predicted and observed values was found to be not significant ($t[7] = 2.1$, $p > .05$, two-tailed). A similar result was found for the actual data obtained for the large

[2] The number of experimental trials depended on the initial staircasing trials. The nominal sample size N is the total number of trials reduced by one less than the number of like responses at the beginning of the series. Because we intended to keep N constant (15), the total number of experimental trials varied (15–17), depending on the initial trials.

[3] The goodness of fit was determined as $R^2 = 1 - [(\Sigma|y_i - F(x_i)|^2)/(\Sigma|y_i|^2)]$, where y_i denotes the actual value and $F(x_i)$ the estimated value, on the basis of the logistic fit.

ball and the predictions derived for this situation, $t(7) = -1.8$, $p > .2$, two-tailed, although the observed shift (17.5%) was somewhat smaller than the predicted 22.0%.

In the derivation of Equation 10, the optical variables were approximated using planar projection of a flat disk approaching at constant velocity. To investigate the effect of these approximations, we calculated the visual angle subtended by the spherical ball as a function of time, taking the changes in velocity during the flight into account (on the basis of a computer simulation of the ball flight). The deviations of the values of $\dot{x}/\dot{r}$ obtained in this way from those obtained using planar projections of a disk approaching at constant velocity increase over lateral passing distance. For this reason, we concentrated on the balls passing at the largest passing distance (1.4 m). During the viewing period $\dot{x}/\dot{r}$ increased. If this quantity was indeed used in the prediction of X_c, the predictions would increasingly overestimate the passing distance (on the average 9%, $SD = 7\%$). However, this overestimation and its variability over time were largely due to the last 150 ms of the viewing period. During the first 450 ms the mean overestimation was 6% ($SD = 2\%$). Analysis of the other passing distances revealed that for the lateral distances up to 1 m the overestimation of X_c on the basis of the rates of change of the visual angles was smaller than 5% (time average, $SD < 4\%$). It is important to note that the differences in ball size did not affect the quantity $\dot{x}/\dot{r}$.

Discussion

Both the direction and the size of the effect induced by introducing alternative ball sizes closely followed the predictions derived on the basis of the information described in Equation 10. These converging results support the hypothesis that passing distance is perceived in units of ball size.

The analysis on the effects of the approximations in the mathematical derivation of Equation 10 revealed that for the balls passing at lateral distances larger than 1 m, these approximations had nonnegligible effects during the last part of the viewing period. However, this cannot account for the observed ball-size effect, for the analysis revealed no differences between the different ball sizes in this respect. We can therefore conclude that the ball-size effect was not related to the effects of the approximations.

Although reliance on object size may seem to be problematic at first glance, it is important to realize that size and distance are optically related quantities. An optically smaller object might be physically smaller or further away. In the absence of additional informational invariants, the only way to estimate distance is by taking the size of the object into account (cf. Gibson, 1979; Saxberg, 1987b). Even if the background is textured, knowledge of either the object's size or the size of the texture elements is required to make absolute spatial judgments. In a number of situations (for instance, in ball games), the size of the object is invariant, which makes the use of object size as a metric for perception of future passing distance viable in these situations at least. In free-flight situations the influence of gravity may provide information about absolute distance and absolute size (Saxberg, 1987a; Watson, Banks, Von Hofsten, & Royden, 1992), which is monocularly perceivable. Moreover, Regan and Beverley (1979) showed that in principle the absolute width of an object is available to the visual system by the combination of changing-size information (monocular) and changing-disparity information (binocular). Perception or knowledge of size is needed to allow appropriate configuration of the hand(s) prior to contact required for successful catching (cf. Savelsbergh et al., 1991).

On the average, subjects overestimated the critical passing distance in the standard situation (112% of maximal sideward reach).[4] This observation is in line with the results of Bootsma et al. (1992). In their study, the subjects performed the task binocularly and indicated the critical passing distance to be at, on the average, 108% of their maximal reach. An explanation of this overestimation can be found in an unnatural aspect of the task: The subjects were not allowed to lean sideward to enhance their reach. With this in mind, we may conclude that they performed reasonably well. The observation that similar results were obtained for monocular and binocular performance suggests that the estimates of future passing distance in both instances were based on the same type of information.

Experiment 2a: Passing Distance, Ball Size, and Angle of Approach

In line with the assumption that future passing distance is perceived in units of ball size, Experiment 1 demonstrated a clear effect of unexpected ball-size manipulation. In addition, the subjects were able to perform the prediction task monocularly, which suggests that a two-dimensional information quantity suffices to estimate future passing distance. In Experiments 2a and 2b, we address the nature of this source of information by presenting simulated trajectories in which the available optical information is reduced to x, r, $\dot{x}$, and $\dot{r}$ (see Figure 1). If, as we hypothesized, $\dot{x}/\dot{r}$ is the optical quantity used, the simulations should provide sufficient information to estimate future passing distance.

Simulations like the present are completely ambiguous with respect to passing distance if both ball size and starting distance are unknown. Knowledge of the ball size used, however, is thought to allow correct perception of passing distance (cf. Saxberg, 1987b). In Experiment 2a, we examined the assumption that observers can accurately judge critical passing distance if the size of the ball simulated is known. We hypothesized that different known ball sizes do not lead to different judged critical passing distances.

If ball size is known, the optical variable $\dot{x}/\dot{r}$ specifies future passing distance for any approach at constant veloc-

[4] The overestimation of reachability was not a consequence of the mathematical approximations; the analysis on the basis of the rates of change of the visual angles subtended by spherical balls indicated that passing distances would have been overestimated, thereby leading to underestimation of reachability.

ity. This implies that differences in direction of motion should not affect the perception of future passing distance. Consequently, balls that will eventually share the same sideward passing distance should be judged as such, irrespective of approach trajectory. This was the second hypothesis we tested in Experiment 2a.

Method

Subjects. Eleven naive subjects (4 men and 7 women) volunteered to participate. Their mean age was 28.3 years (range = 20–41). Mean maximal sideward reaching distance was 83.3 cm (SD = 3.7 cm). All reported normal or corrected-to-normal vision.

Experimental set-up. The displays were obtained by calculating the successive optical positions and sizes of the (spherical) ball on the projection plane, for each given trajectory. These optical variables were projected on a large screen subtending 60° horizontally × 49° vertically of visual angle, using a video projector (Electrohome 3001) connected to a high-resolution (1,280 × 1,024 pixels) graphics board (MATROX SM1281). Frame rate was 50 images/s, resulting in smooth apparent motion. Simulated flight height of the ball was kept constant at 1.6 m.

The simulated trajectories started at an 8-m distance from the fronto-parallel plane of the observer and the balls approached this plane following different trajectories. The forward velocity component was always 4 m/s and the sideward velocity component could be either −0.15 m/s or 0.15 m/s, leading to trajectories that differed, respectively, 2.15° ("inward") or −2.15° ("outward") from being perpendicular to the fronto-parallel plane (see Figure 4).[5] The 12 inward trajectories started at different distances to the right of the line of sight, ranging from 0.6 m to 1.7 m, separated by 0.1-m intervals. Each inward trajectory crossed the fronto-parallel plane 0.3 m closer to the line of sight than it had started, which resulted in 12 passing distances ranging from 0.3 m to 1.4 m. These passing distances were shared with the 12 outward trajectories, the starting positions of which ranged from 0 m to 1.1 m sideward distance, also separated by 0.1-m intervals.[6]

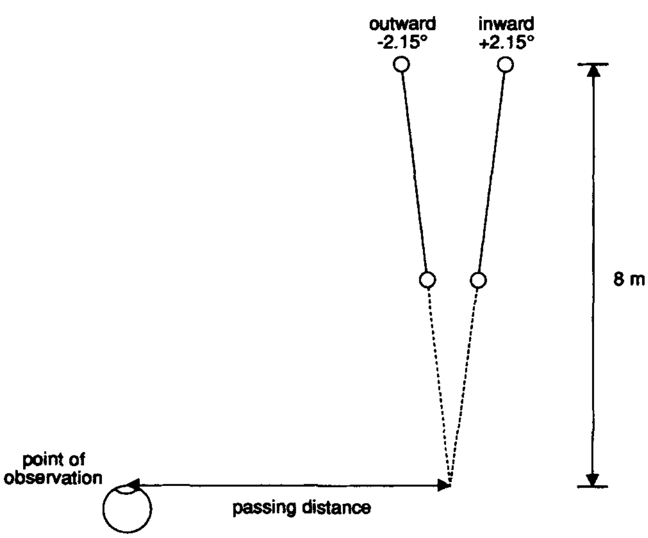

Figure 4. Schematic representation of Experiment 2a: two trajectories passing at the same distance.

Four different ball sizes were simulated: 2.5 cm, 5 cm, 10 cm, and 20 cm (diameters). Each approach was only visible for the first second.

Procedure. The subject was seated 3.2 m in front of the screen on a 1-m high chair so that the balls approached approximately at eye level. The experimenter explained that the presentation of the simulated ball trajectories would be terminated before the ball passed the subject. The subject's task was to indicate verbally whether it would be possible to touch the passing ball by only stretching the right arm to reach for it and, thus, without sideward leaning to enhance maximal reach. The judgments were not to be accompanied by an actual reaching movement.

A session consisted of four blocks, in each of which one of the four ball sizes was presented. Prior to each block, the subject was given a full-scale cardboard model representing the size of the simulated ball. During a block, each trajectory was presented 10 times, resulting in 240 trials per block; the blocks were randomly ordered. Each block was run in a completely darkened room and took about 9 min. Between blocks the subject was allowed to take a short rest. During these breaks the room lights were turned on. The sequence of the ball size blocks was randomly ordered over the subjects.

The subjects were tested twice, on different days. On the first test day a practice block was presented prior to each experimental block. In these practice blocks the ball to be tested was presented in 48 trials (24 trajectories × 2 repetitions). As in the experimental situation, no feedback on the judgments was ever provided.

Results

A preliminary 12 (passing distance) × 4 (ball size) × 2 (angle of approach) × 2 (test day) repeated measures ANOVA was performed on the percentage of balls judged to be unreachable. Passing distance turned out to account for almost 70% of the total variance, between subject variability for 8%, and the other factors for less than 2.5% each. The analysis showed significant main effects for passing distance, $F(11, 110) = 147.8$, $p < .001$; ball size, $F(3, 30) = 13.0$, $p < .001$; and angle of approach, $F(1, 10) = 35.7$, $p < .001$. It also showed significant interaction effects for Ball Size × Angle of Approach, $F(3, 30) = 9.0$, $p < .001$; Ball Size × Passing Distance, $F(33, 330) = 7.9$, $p < .001$; and Angle of Approach × Passing Distance, $F(11, 110) = 3.8$, $p < .001$. The difference between the test days was not significant, $F(1, 10) = .03$, $p > .2$.

These results showed that the judgments on reachability were not the same for balls passing at different sideward distances, indicating that the subjects indeed perceived differences in passing distance. Furthermore, the two factors of interest in this experiment, Ball Size and Angle of Approach, both showed significant effects, although these were

[5] Note that the simulated angles of approach did not deviate much from being perpendicular to the fronto-parallel plane. Therefore, it was not possible for the subjects to distinguish accurately the inward from the outward trajectories when confronted with the simulated situation.

[6] The passing distances, trajectories, and viewing period were chosen in such a way that the approximation of the optical information, using planar projections of approaching disks, was appropriate.

Table 1
The Average Values (Vs) and Standard Deviations of the Scaled Judged Critical Passing Distances (Percentage of Maximal Sideward Reach) for Each Combination of Ball Size (in Centimeters) and Trajectory

	Ball size									
	2.5		5		10		20		*M*	
Trajectory	*V*	*SD*	*V*	*SD*	*V*	*SD*	*V*	*SD*	*V*	*SD*
Outward (−2.15°)	81.9	24.5	93.9	20.2	104.1	20.8	99.4	20.7	94.8	22.5
Inward (2.15°)	70.3	21.1	80.1	19.9	87.0	18.7	78.6	21.4	79.0	20.5
M	76.1	23.1	87.0	20.8	95.6	20.3	89.0	23.1		

not expected to occur if the judgments were based on the information quantity $\dot{x}/\dot{r}$. Because the judgments did not differ over test days, further analysis was performed without distinguishing between the two sessions.

The passing distance at which the percentage of unreachable judgments reached 50% was taken to be the judged critical passing distance and determined by fitting each observer's data to the logistic equation (Equation 11). Note that a ball may already be judged to be reachable if only the closest edge can be touched. In the present context, the judged critical distances were thus indicative of the estimated future passing distance of the closest edge, instead of the center of the ball. Because the differences in diameter were considerable (2.5–20 cm), the obtained critical distance had to be corrected for ball size: The judged critical passing distance was reduced by half the ball size before it was scaled to the subject's maximal reach.

For all subjects the data showed good fits with the logistic function for all conditions (R^2 ranging from .92 to 1.00). The mean scaled judged critical passing distances are presented in Table 1.[7] A 2 (angle of approach) × 4 (ball size) repeated measures ANOVA on scaled judged critical distance revealed that between-subject differences were substantial, accounting for 57% of the total variance, whereas the treatment effects accounted for 22% of the variance. The factor Angle of Approach turned out to have significantly affected the estimates, $F(1, 10) = 33.7$, $p < .001$. The scaled judged critical passing distances obtained for the outward trajectories were significantly larger than those obtained for the balls moving inward. In addition, a significant ball size effect was found, $F(3, 30) = 5.2$, $p < .005$. Post hoc analysis (Newman-Keuls, $p < .05$) revealed that this effect was due to the 2.5-cm ball giving rise to smaller critical distances than the other three balls. The interaction effect also was significant, $F(3, 30) = 5.7$, $p < .005$. This effect was caused by the relatively large difference between the critical distances obtained for the 20-cm ball (Newman-Keuls, $p < .05$).

The magnitude of the slope at the critical point of the fit to the logistic function may provide information about the subject's confidence in judgment (Bootsma et al., 1992): The steeper the function, the more certain the subject was. The slopes obtained for the critical points of the fits were therefore also analyzed in a 4 (ball size) × 2 (angle of approach) repeated measures ANOVA. The results showed that intersubject differences accounted for 12% of the total variance, and the treatment effects for 10%. No significant effects were observed.[8]

Discussion

The first hypothesis examined in this experiment held that observers can accurately judge critical passing distance if the size of the simulated ball is known. To this end, the subjects were informed of the ball size used by means of a full-scale cardboard model. Contrary to our expectations, the results indicated an effect on the estimation of future passing distance induced by differences in the simulated ball size. The effect of ball size on judged critical passing distance, however, was solely due to the smallest ball (2.5 cm). It is likely that the projection resolution was not sufficient to allow adequate simulation of the low rate of absolute expansion for this small ball. During the display the projected size increased on the average with 0.01 m/s, resulting in an average angular rate of change of 0.18°/s. As a consequence of this low rate of expansion, the projected ball size (r) was only increased three times during the display time (1 s). It is, therefore, quite likely that the subjects had problems with perception of motion in depth. Because no effect was observed for the other ball sizes, we assume that the 2.5-cm ball was too small for adequate motion simulation under the conditions of this experiment. Therefore, we will not regard this ball-size effect as evidence against the hypothesis that passing distance is perceived in units of ball size. Moreover, the observation that the other three ball sizes did not lead to differences in judgment (the subjects being aware of the size of the ball presented) supported this hypothesis.

The results clearly demonstrated that angle of approach had an effect on the perception of future passing distance.

[7] The scaled judged critical distances obtained in this experiment were, on the average, smaller than those found in Experiment 1 and those reported by Bootsma et al. (1992). This difference could be due to the use of simulated approaches or to the subjects' being seated in this experiment.

[8] It should be noted that, although the sample range was chosen fairly symmetrical around the 50% point, the slopes and their variability obtained using the logistic fit may be affected by the small sample size (O'Regan & Humbert, 1989).

Balls moving outward with respect to the observer were judged to pass closer by than those moving inward, thereby leading to a larger scaled judged critical distance for the former than for the latter. The analysis on the slopes at the 50% point of the logistic fits showed no difference between the angles of approach. This result implied that the judgments were simply shifted with respect to each other. A difference in slope would have indicated a difference in confidence (cf. Bootsma et al., 1992).

Because $\dot{x}/\dot{r}$ was the same for each set of two trajectories sharing a passing distance, the angle of approach effect on the reachability threshold was at odds with the assumption that human observers use (only) this optical quantity in their estimation of passing distance. On what alternative source of information might their judgments be based? In the simulations presented in Experiment 2a only four simple optical variables and, of course, the different possible combinations thereof, were available. For each ball size three of the simple optical variables (r, $\dot{r}$, and $\dot{x}$) were the same for both trajectories converging onto the same passing distance. Hence, the differences found could be due to variations in the optical variable that was not the same over these trajectories: optical sideward distance x. We designed Experiment 2b to investigate this possibility.

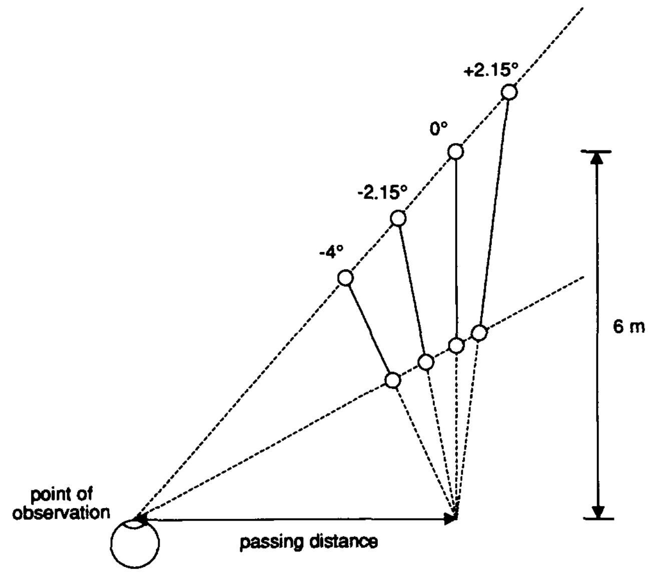

Figure 5. Schematic representation of Experiment 2b: four trajectories passing at the same distance. The starting distances and approach velocities of the balls were chosen in such a way that the initial and final projected sideward distances were equal for all four trajectories.

Experiment 2b: Passing Distance and Angle of Approach

In Experiment 2b, simulated approach trajectories were used. The trajectories and approach velocities were chosen such that the average values of x, $\dot{x}$, and $\dot{r}$ were the same for the different trajectories sharing a passing distance. If indeed variations in the optical sideward distance x had been the cause of the angle of approach effect on judged critical passing distance in Experiment 2a, this effect should not emerge under the present conditions.

Note that the average optical ball size r did vary over the different trajectories in Experiment 2b. However, the previous experiment had shown that optical ball size does not affect the judgment (as long as the ball is large enough for adequate motion simulation): differences in r do not lead to differences in reachability judgments, provided that ball size is known.

Method

Subjects. Eight of the subjects tested in Experiment 2a (four men and four women) volunteered to participate. Their mean age was 28.7 years, their ages ranged from 20 to 41 years, and their mean maximal sideward reach was 84.1 cm (*SD* = 3.8 cm).

Experimental set-up. The simulations were generated using the same equipment as in the previous experiment. Only a 10-cm diameter ball was simulated. The simulated trajectories crossed the fronto-parallel plane at 10 different passing distances (0.5 m to 1.4 m to the right of the observer; increment: 0.1 m). Each passing distance was shared by four trajectories that differed in obliqueness (−4°, −2.15°, 0°, and 2.15°), resulting in 40 unique trajectories. The balls following the perpendicular (0°) trajectories always started at a 6-m distance from the fronto-parallel plane and traveled at 4 m/s. The starting points and velocities of the oblique trajectories were chosen in such a way that all trajectories converging onto the same passing distance were equal with respect to the values of x for both starting position and cut-off position (position in last frame) and, thus, to average optical sideward velocity $\dot{x}$ (see Figure 5). Because $\dot{x}/\dot{r}$ was the same for all four trajectories that passed at the same distance, the average value for $\dot{r}$ did not differ over these trajectories either. This average rate of expansion was 0.97°/s, which, according to the results of Experiment 2a, was large enough to avoid an effect due to small values of $\dot{r}$. Display time was reduced to 0.5 s, in order to keep the differences in x, $\dot{x}$, and $\dot{r}$, as a function of time, to a minimum.[9]

Procedure. The procedure was similar to that followed in Experiment 2a. However, because only one ball size was to be considered, the 400 trials (40 trajectories × 10 repetitions) were presented in a single randomized block. A short break was given halfway through this block. Prior to the session the subject was notified of the ball size by means of a cardboard model. As in Experiment 2a, the subjects were tested twice, on different days. On the first test day, prior to the experimental session, the experimenter explained that the balls came from different distances and at different velocities, and in a short practice block all 40 trajectories were presented once. Feedback was never provided.

Results

A preliminary 10 (passing distance) × 4 (angle of approach) × 2 (test day) repeated measures ANOVA on the reachability judgments revealed that passing distance ac-

[9] The passing distances, trajectories, and viewing period were chosen in such a way that the approximation of the optical information, using planar projections of approaching disks, was appropriate.

counted for almost 70% of the total variance; intersubject differences accounted for 13% and each of the other factors for less than 2%. Significant effects were shown to exist for Passing Distance, $F(9, 63) = 62.5$, $p < .001$; Angle of Approach, $F(3, 21) = 29.9$, $p < .001$; and for the interaction between these two factors, $F(27, 189) = 3.4$, $p < .001$. Performance on the 2 test days did not differ significantly, $F(1, 7) = 1.8$, $p > .2$.

In line with the results of Experiment 2a, balls that passed at different distances induced different reachability judgments. Although the direction of motion was not supposed to influence the estimation now that the optical sideward distance x was, on the average, the same for trajectories sharing a passing distance, the significant Angle of Approach effect indicated the contrary. Because the factor Test Day showed no significant effect, the following analyses were conducted without distinguishing between the 2 test days.

The scaled judged critical passing distances and the slopes at the 50% points of the fits were obtained in the same way as in the previous experiments. For all subjects the data showed good fits with the logistic function, for all conditions (R^2 ranging from .84 to 1.00).

A repeated measures ANOVA with the factor Angle of Approach (4) on scaled judged critical passing distance showed that the differences between the subjects were large, accounting for 63% of the total variance; 19% of the total variability was explained by the factor Angle of Approach. The effect of Angle of Approach proved to be significant, $F(3, 21) = 7.4$, $p < .005$. Figure 6 reveals that, on the average, the scaled judged critical distance increased over the angles of approach (−4° to 2.15°). Regression analysis showed a significant linear relation between scaled judged critical distance and Angle of Approach ($R^2 = .93$).

No significant effects were obtained in a repeated measures ANOVA with the factor Angle of Approach (4) on the

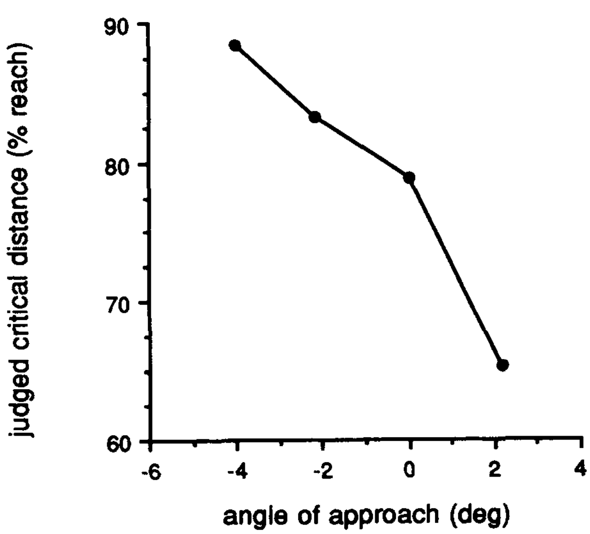

Figure 6. Mean scaled judged critical passing distance as a function of angle of approach. (Deg = degree; mean *SD* = 15.8%.)

slopes at the critical points of the logistic fits, in which intersubject differences accounted for 16% and the factor Angle of Approach for 12% of the total variance.

To compare the −2.15° and 2.15° trajectories for both simulation experiments (Experiments 2a and 2b), we performed a 2 (angle of approach) × 2 (experiment) repeated measures ANOVA on the critical distances obtained for these trajectories in Experiment 2b and those obtained for the 10-cm ball in Experiment 2a for the 8 subjects who had participated in both experiments. Between-subject differences turned out to explain 65% of the total variance, and the treatment effects 21%. The results showed no significant difference between the two experiments, $F(1, 7) = 4.4$, $p > .05$. The −2.15° and 2.15° trajectories led to significantly different judged critical passing distances (on the average, 93% and 76% of maximal reach, respectively), $F(1, 7) = 111.9$, $p < .001$. No significant interaction effect was found to exist, $F(1, 7) = 2.1$, $p > .15$.

Discussion

Similar to what was found in Experiment 2a, the angle at which the ball approached was found to affect the perception of future passing distance. Because no effects on the slopes at the critical points of the fits were found, we may conclude that the differences in judgment observed were not the result of a change in confidence (cf. Bootsma et al., 1992).

As mentioned before, the observation that the angle at which the ball approached the observer's fronto-parallel plane affected the estimation of future passing distance did not support the assumption that the estimation of passing distance is based (solely) on $\dot{x}/\dot{r}$. In Experiment 2a, optical sideward distance x was the only simple optical quantity that varied over the angles of approach. If the effect of angle of approach observed in Experiment 2a was due to the variations in this optical variable, then simulated ball flights that shared a passing distance and were (on the average) equal with respect to x, should have been judged as passing at the same distance. However, the results of Experiment 2b demonstrated the contrary. Moreover, because neither the main effect of the factor Experiment nor the interaction effect turned out to be significant, comparison of Experiments 2a and 2b with respect to the −2.15° and the 2.15° trajectories indicated that in the two experiments the angle of approach had induced similar effects on estimation of future passing distance.

It seems reasonable, therefore, to assume that in both experiments the angle of approach effect was caused by the same factor. However, investigation of the variables varying over the trajectories passing at the same distance: In Experiment 2a optical sideward distance (x) varied and in Experiment 2b optical ball size (r) varied. Neither of them alone can account for the effects. It is possible, though, that the estimations were based upon the relation between the two.

The optical quantity x/r specifies momentary sideward distance (X) in terms of ball size (R). This quantity was constant and, thus, predictively specifying future passing distance, only for trajectories perpendicular to the observer's fronto-parallel plane. For an outward moving trajectory, X (and hence x/r) was always smaller than the future passing distance (expressed in units of ball size) even though it was increasing, whereas for inward motion it always was larger though decreasing. The results showed that subjects tended to perceive outward trajectories as passing closer by than inward trajectories. This suggests that their judgments might have been influenced by the optical quantity x/r. However, by the end of the display period, the differences in $(x/r) \times R$ were still considerably larger than the observed differences in judged critical distances. This implies that the judgments were not simply based upon the last available information specifying current sideward distance.

As x/r provides instantaneous information, subjects may be able to use its evolution over time to anticipate passing distance. The information quantity

$$\frac{X_c}{R} = \frac{x}{r} + \frac{d(x/r)}{dt}\tau, \tag{12}$$

where $d(x/r)/dt$ specifies the rate of change of x/r over time and τ is the optical variable specifying time-to-contact, specifies future passing distance of nonaccelerative approaches at any moment in time. Correct perception of τ leads to Equation 10. Underestimation of time-to-contact, however, would lead to the qualitative features of the angle of approach effect observed in Experiments 2a and 2b. Indeed, a number of studies in which the viewing period was terminated before the object actually arrived at the point of observation, demonstrate underestimation of the time remaining until arrival (e.g., Cavallo & Laurent, 1988; McLeod & Ross, 1983; Schiff & Detwiler, 1979; Schiff & Oldak, 1990). This hypothesis, that the angle of approach effect was due to an underestimation of time remaining, was addressed in Experiment 3.

Experiment 3: Passing Distance and Estimation of Time-to-Contact

If, as suggested above, the observed angle of approach effect was the result of an underestimation of time-to-contact, this effect will be larger if the time remaining until the ball passes is larger (cf. Schiff & Detwiler, 1979). To investigate this prediction, the viewing periods during which the subject could see the balls and the remaining time-to-arrival at the fronto-parallel plane were manipulated in this experiment. In addition, the angle at which the ball approached the fronto-parallel plane was manipulated.

Alternatively, the angle of approach effect observed in the two simulation studies (Experiments 2a and 2b) might be due to insufficiency of the available information. To test whether the effect found was caused by the fact that the approaching balls were simulated, we presented real approaching balls in this experiment. Moreover, subjects performed binocularly.

To get a better picture of the estimations of future passing distance, the subjects were required to manually indicate this distance. In this way an estimation for each approaching ball was obtained, resulting in a range of estimations for each condition, whereas in the previous experiments only the judged critical passing distance was available for analysis.

Method

Subjects. Ten subjects (5 men and 5 women) participated (mean age = 27.4, range = 21–34). All reported normal or corrected-to-normal vision.

Experimental set-up. We used the set-up that was described for Experiment 1. The subject was positioned 0.7 m further backwards, so that the ball reached its lowest point 2 m in front of the subject's fronto-parallel plane. Flight time until the ball passed the subject, at 1.4 m height, was about 1.55 s.

The suspension points of the fishing lines that supported the balls were chosen in such a way that 5 balls would pass the subject at a distance 0.64 m to the right, and the other 5 at 1.02 m to the right. Thus, each of the two passing distances was approached at 5 different angles. The angles of approach at the 0.64-m passing distance were −3.6°, −2.4°, −1.2°, 0°, and 1.2° relative to the perpendicular to the fronto-parallel plane. The trajectories passing at the 1.02-m distance were the mirror images of these angles: −1.2°, 0°, 1.2°, 2.4°, and 3.6°. In this way the total range of angles of approach was −3.6° to 3.6°.

To control the viewing periods, the subject wore the LCD goggles, which could be made to change from opaque to transparent and back to opaque. The glasses and the release mechanism of the balls were both controlled by a single Olivetti M24 microcomputer to secure optimal synchronization.

Indications of future passing distance were scored using a measurement construction, which consisted of a handle attached to a rail. This handle could be moved freely to the right to any position within a range of 2.5 m. The final handle position could be obtained from a ruler attached to the rail.

Procedure. The subject was positioned at a predetermined starting point, holding the positioning handle in the right hand (also at a fixed position), and was instructed to move the handle to the position that corresponded with his or her estimation of the distance at which the ball passed. After each trial the subject was escorted back to the initial position and the ball was thrown up and repositioned. Feedback was not provided.

Three viewing periods were used: 500–800 ms ("early"), 900–1,200 ms ("late"), and 500–1,200 ms ("long") after ball release. During these periods both glasses were transparent, thus allowing binocular vision. Average angular expansion rate was 0.43°/s in the early condition and more than 1°/s in the other two.[10]

During a block of trials all 10 balls were released one by one in a randomized order. For each viewing condition three blocks were presented (30 trials total) as subsessions. The viewing sessions were semicounterbalanced over the subjects. Between the subsessions the goggles were removed and the subject could rest. Prior to

[10] The passing distances, flight trajectories, and viewing periods were chosen in such a way that the approximation of the optical information, using planar projections of approaching disks, was appropriate.

the first block, the subject was acquainted with the task through a series of 10 practice trials. The experiment took about 75 min/subject.

Results

The constant error (CE; in centimeters) was determined for every condition for each subject, calculated over the three replications. In all cases the passing distances appeared to be, on the average, overestimated.

First, the CEs for the three angles of approach (−1.2°, 0°, 1.2°) that were common to both passing distance conditions were analyzed in a repeated measures ANOVA with the factors Viewing Period (3), Passing Distance (2), and Angle of Approach (3). Between-subject differences were substantial (74% of the total variation), whereas treatment effects accounted for only 5.4% of the total variability. Nevertheless, the main effect for the factor Angle of Approach was found to be significant, $F(2, 18) = 6.5$, $p < .01$. The CEs increased over the range of Angles of Approach (from −1.2° to 1.2°: 13.1, 14.6, and 18.7 cm).

The Viewing Period × Passing Distance interaction was also found to be significant, $F(2, 18) = 5.6$, $p < .05$. Post hoc Newman-Keuls comparison showed that this effect was solely due to the estimates made for the 1.02-m passing distance in the early viewing condition ($p < .01$). In this situation the mean CE was significantly smaller than in all other situations. The factor Viewing Period itself did not reach significance, $F(2, 18) = 2.5$, $p > .1$.

Second, a 3 (viewing period) × 5 (angle of approach) ANOVA on the CEs observed for the trajectories passing at the 0.64-m sideward distance was performed. Again, intersubject variation turned out to be large (70%). The treatment effects accounted for 13% of the total variance. The angles of approach significantly affected the judgments, $F(4, 36) = 9.6$, $p < .001$. The mean CE showed a linear increase over the angles of approach ($CE = 17.2 + 2.2 \times \text{angle}$; $R^2 = .99$). The Angle of Approach × Viewing Condition interaction was also found to be significant, $F(8, 72) = 2.3$, $p < .05$. For each viewing period considered individually, the Angle of Approach had a linear effect on mean CE. This increase was by far the strongest if the ball was visible early in its flight, whereas the other two viewing conditions did not differ much in this respect, as can be seen in Figure 7A. The factor Viewing Period approached significance, $F(2, 18) = 3.0$, $p < .1$.

The last 3 × 5 ANOVA addressed the judgments obtained for the trajectories passing at the 1.02-m sideward distance. As in the former two analyses, between-subject variation accounted for most of the total variability (80%); treatment effects accounted for 9% of the total variance. The effect of angle of approach was significant, $F(4, 36) = 15.9$, $p < .001$, resulting from a linear increase in mean CE over the angles of approach ($CE = 14.1 + 2.9 \times \text{angle}$; $R^2 = .94$, see Figure 7B). The effect of the viewing period again approached significance, $F(2, 18) = 2.8$, $p < .1$.

Discussion

As was observed in the simulated situations of Experiments 2a and 2b, angle of approach was found to have a strong effect upon the estimation of future passing distance in Experiment 3. Note that, because the subjects were judging future passing distance instead of reachability in this experiment, the increase in judged passing distance as a function of angle of approach reflected an effect similar to that indicated by the decreasing judged critical distance in the reachability studies.

In the present experiment, the subjects performed binocularly in a real approach situation; thus, it is very unlikely that the angle of approach effect was due to insufficient information. The similarity between the present results and those of the simulation studies suggested that even if subjects performed binocularly they relied on optical information such as angular size, angular position, and their derivatives, in estimating future passing distance.

The effect of the viewing period was not very clear-cut. The main effect of this factor showed a tendency toward significance, but it never reached the .05 significance level. The predicted interaction effect between viewing period and angle of approach was found in two of the three analyses. The increase in CE as a function of angle of approach was stronger if the early part of the trajectory alone was visible. In other words, the angle of approach effect was the strongest if time-to-contact was the largest. If the angle of approach effect was caused by an underestimation of time-to-contact, this is what we would expect to find.

The slopes of the linear fits to the observed mean CEs as a function of angle of approach did not differ much for the late and long viewing conditions (see Figure 7). Because the time remaining until contact after the display was equal in these two conditions, this finding also was in line with the hypothesis that the angle of approach effect was due to underestimation of time remaining.

Hence, the results of Experiment 3 provided some support for the hypothesis that the angle of approach effect was caused by underestimation of time-to-contact. However, because the expected interaction effect between angle of approach and viewing condition was not observed for the estimates obtained for the balls passing at 1.02 m, the results were not completely unproblematic with respect to the hypothesis. Further experimentation was required to unravel the role played by the estimation of time-to-contact in the demonstrated effect of angle of approach.

Experiment 4: Time-to-Contact Is Not Underestimated!

The rationale behind Experiment 3 was that the angle of approach effect could be due to underestimation of time-to-contact. Although the results pointed in this direction, however, they were not completely convincing. A new experiment was designed to further explore the relation between estimation of time-to-contact and estimation of future passing distance. In this experiment, the subjects were required

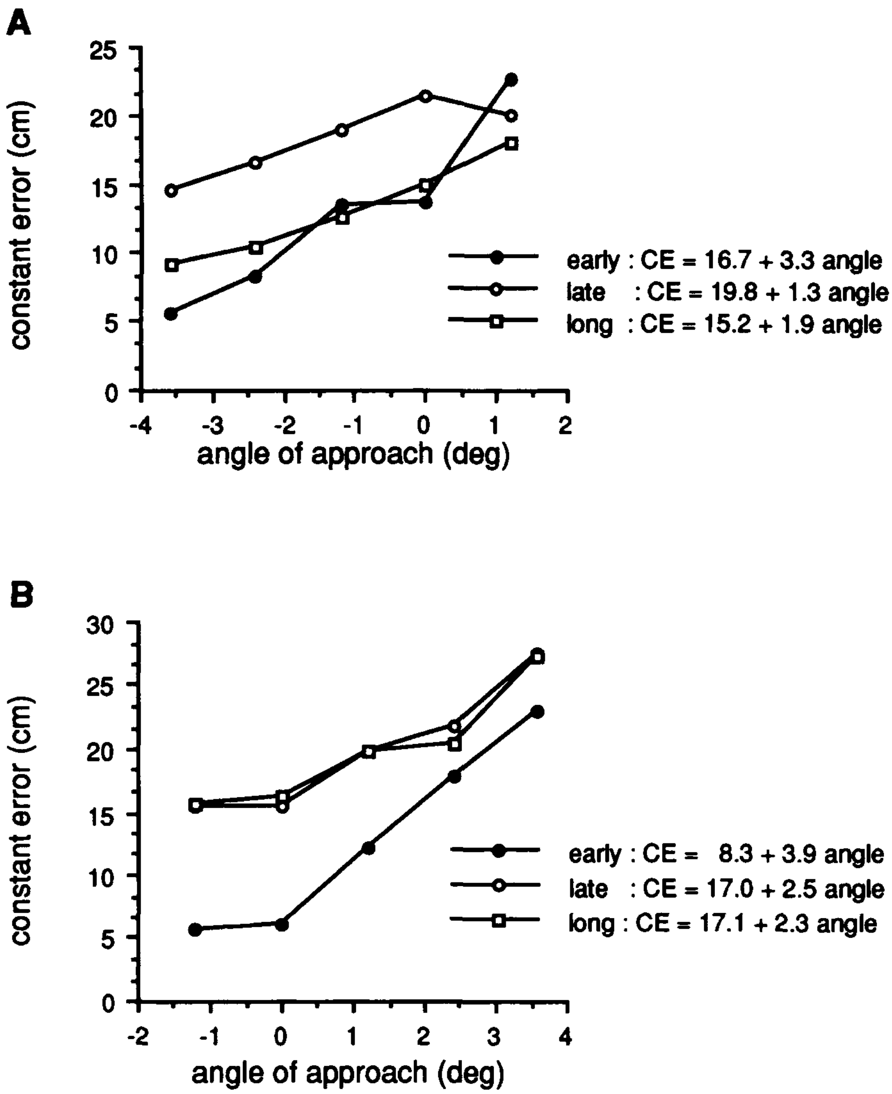

Figure 7. Mean constant error (CE) as a function of angle of approach, for each viewing condition. A: Results when the passing distance was 0.64 m (mean *SD* = 25.1 cm); B: Results when the passing distance was 1.02 m (mean *SD* = 15.5 cm). Deg = degree.

to try to really catch approaching balls, while angle of approach and the time remaining from the end of the viewing period were manipulated. Analysis of both the moment at which the hand was closed (indicating the moment of intended catch) and the hand position at this moment, was expected to reveal the relation between the spatial angle of approach effect and expected temporal effect of the time remaining until contact. On the basis of the assumption that the angle of approach effect was due to underestimation of the time remaining, it may be predicted that the magnitudes of these two effects are positively related.

In order to distinguish between a spatial and a temporal aspect of the task, the hand was constrained to move parallel to the observer's fronto-parallel plane. This implies that for each approach condition the combination of hand position and catching moment required for a successful catch was known a priori.

Method

Subjects. Ten right-handed subjects (3 men and 7 women) participated. Their mean age was 26.1 years (range = 19–38). All reported normal or corrected-to-normal vision.

Experimental set-up. The apparatus used in Experiments 1 and 3 was used. Only six trajectories were presented. Two balls approached perpendicular (0°) to the subject's fronto-parallel plane, passing at either 0.40-m or 0.77-m distance to the right of the subject (at a height of 1.6 m). The latter passing distance was shared by the four other balls, approaching at angles of –2°, –1°, 1°, and 2°. The balls traveled a distance of 7.23 m, with a flight time of 1.623 s. The differences in angle of approach were too small to affect the duration of the ball flight. The lowest point (1 m) was reached at 2.34 m in front of the subject.

The moment of the hand closing was determined by means of an optoreflector (sampling rate 200 Hz), which was positioned at the end of a thin metal support (6 cm long). This support was attached to the subject's hand in such a way that reflection of the middle finger was maximal if the hand was fully opened and minimal if it was closed. To enhance reflection the subject wore white vinyl gloves.

The hand movements were registered using a Multi Infrared LED (light-emitting diode) Control Unit (MILCU; Den Brinker, Krol, & Zevering, 1985), consisting of a microcomputer (Olivetti PCS 286) coupled to a Selcom 413-3 camera. An infrared LED was positioned near the middle of the hand (at the dorsal side of *os metacarpale II* near the *m.c.p.*-joint), in such a way that it was visible for the camera hanging above the subject. The position signal was sampled at 200 Hz.

To control the viewing period, the subject wore LCD glasses. The release mechanism of the balls, the LCD goggles, and the optoreflector were all controlled by the microcomputer belonging to the MILCU system to secure optimal synchronization (using the FAMS-lab system; Den Brinker & Coolen, 1993).

In their catching action, the subjects moved the right hand along a horizontal bar. In this way the hand movements were constrained to the sideward direction at the correct catching height.

Procedure. In the experiment, the subject stood at a designated position holding the right hand a little in front against the bar. The instruction was to catch the approaching ball by moving the hand along the bar. The subject was allowed to make sideward steps if desired. Flight time in all trials was equal; the experimenter prevented the subject from anticipating the moment at which the ball would pass by varying over trials the time between the verbal indication to the subject that the ball was going to be released and the moment that this actually happened.

The subjects performed binocularly. The viewing period, which lasted for 300 ms, was presented at three different moments during the flight time: 500–800 ms ("early"), 800–1,100 ms ("middle"), and 1,100–1,400 ms ("late") after ball release.[11] Hence, the time remaining until the ball passed the subject was 823 ms, 523 ms, and 223 ms, respectively. The resulting 18 conditions (3 viewing conditions × 6 trajectories) were all presented five times in a randomized order (90 trials total). Halfway through the experiment, the subjects were allowed a short rest, during which the glasses were taken off. Running the experiment took about 75 min/subject.

Prior to the experiment, the subject caught 10 balls without wearing the glasses. The trajectory used in this instance approached at an angle of 0°. (The subject stood at a position other than that in the experimental trials.) Next, he or she put on the LCD glasses. A sample of 9 selected experimental trials (3 viewing conditions × 3 trajectories) was presented once for practice.

Analysis. The data obtained for the ball approaching perpendicular to the fronto-parallel plane at 0.4 m (the distance that was not shared by the oblique trajectories) were not analyzed, because they only served to keep the subject from noticing a single passing distance. The moment of maximal closing velocity of the hand was taken as the measure of the moment of catch (cf. Savelsbergh et al., 1991).

The MILCU data were filtered (10 Hz, recursive second-order Butterworth filter). From the optoreflector data the moments of maximal closing velocity were obtained. The hand positions at these moments were derived from the MILCU data. For each condition and for each subject, the CE of the hand position with respect to the target passing distance was determined as well as the mean moments of maximal closing velocity.

Results

A 3 (viewing period) × 5 (angle of approach) ANOVA with repeated measures on the CE in the position of the hand at the moment of maximal closing velocity revealed that between-subject variation accounted for 24% of the total variation and the treatment effects for 51%. Both factors and the interaction between them revealed significant effects; for Viewing Period, $F(2, 18) = 19.1$, $p < .001$; for Angle of Approach, $F(4, 36) = 35.8$, $p < .001$; and for Viewing Period × Angle of Approach, $F(8, 72) = 8.0$, $p < .001$.

The mean CE changed as the viewing periods were presented later (t_c from 823 ms to 223 ms: −19.0, −7.0, and −2.3 cm, respectively). This change in CE reflects the fact that the hand positioning became more accurate as the time remaining until the ball passed, after the glasses had turned opaque again, was smaller.

The mean CE increased linearly over the range of angles of approach (from −2° to 2°: −14.7, −11.1, −8.3, −7.6, and −5.5 cm; $CE = -9.4 + 2.2 \times \text{angle}$; $R^2 = .95$). In Figure 8 the mean CE is presented as a function of angle of approach for each viewing period separately. Post hoc comparison (Newman-Keuls, $p < .05$) indicated that only the late viewing period did not reveal any significant differences over the presented angles. The three values found for the 0° trajectories did not differ significantly from one another.

A 3 (viewing period) × 5 (angle of approach) ANOVA with repeated measures performed on the moment of maximal hand closing velocity showed that intersubject variation accounted for 32% and the treatment effects for 11% of the total variation. No significant effects were found to exist, although the factor Angle of Approach tended toward significance, $F(4, 36) = 2.5$, $p < .06$. However, this effect turned out not to be systematic, as can be seen in Table 2.[12]

Discussion

The results of the ANOVA on the CE in the hand position at the moment of catch revealed that, in the spatial domain, the observations are similar to the effects described previously. The fact that the viewing moment did not have a significant effect upon the moment of maximal hand-closing velocity, however, implied that time-to-contact was not underestimated. Thus, this observation contradicted the hypothesis that the angle of approach effect was due to underestimation of time-to-contact.

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[11] The flight trajectories and viewing periods were chosen in such a way that the approximation of the optical information, using planar projections of approaching disks, was appropriate.

[12] Table 2 shows that, although no significant differences between the viewing periods were observed, the variation in the "early" condition was larger than in the other conditions. This difference may reflect a difference in certainty about time-to-contact when the time remaining was large.

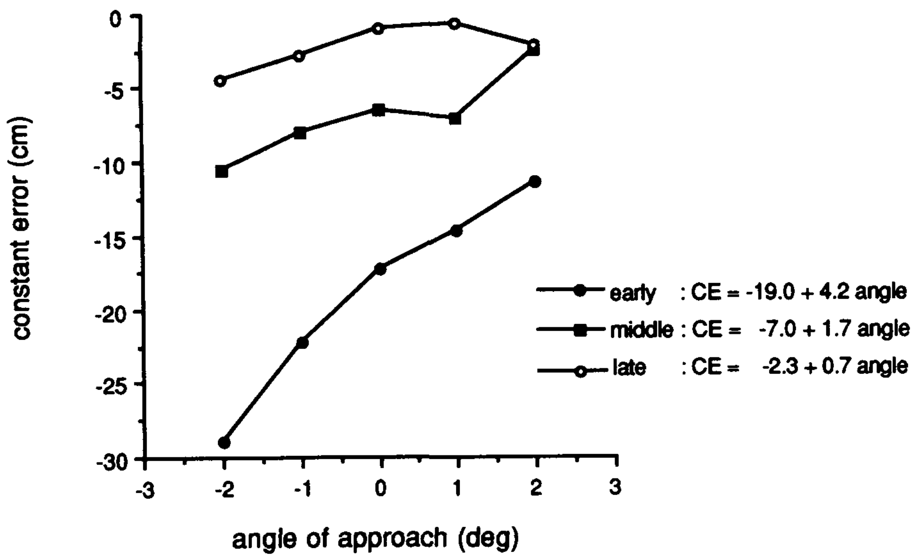

Figure 8. Mean constant error (CE) for each viewing condition (early, middle, and late) as a function of angle of approach (mean *SD*s = 11.7 cm, 7.7 cm, and 2.9 cm for early, middle, and late viewing condition, respectively). Deg = degree.

In the preceding four experiments, using both simulations and real approaches, the angle at which the ball approached the subject's fronto-parallel plane was found to have a significant effect upon the judgment on passing distance. The results of Experiments 2a and 2b indicate that this effect might have been related to the optical variable x/r. It was hypothesized that the subjects used this quantity's evolution over time in their estimation of future passing distance, and that the observed effect was caused by underestimation of the time remaining until the ball passed. However, although the angle of approach effect was the largest if the time remaining was the largest (Experiments 3 and 4), the effect was not due to underestimation of this time-to-contact, as was demonstrated in Experiment 4.

We therefore conclude that neither of the two proposed sources of optical information (Equation 10 and Equation 12) were used in the estimation of future passing distance. The results of the two simulation studies (Experiments 2a and 2b) suggested nevertheless that the optical quantity x/r played a role in these estimations, although the subjects did not simply rely on only this source of information. This variable specifies momentary sideward distance in units of ball size, and, thus, does not predict future passing distance. In the last experiment to be presented (Experiment 5), we investigated the possibility that subjects depend on an instantaneous source of information relating to momentary sideward distance, instead of information specifying a future position.

Experiment 5: Continuous Guidance of the Lateral Hand Movement

In Experiments 2–4, we found that the manipulation of angle of approach always affected the prediction of future passing distance. The angle of approach effect was larger if the period between the moment that the ball was no longer visible and the moment that it broke the observer's fronto-parallel plane was larger (Experiments 3 and 4). However, this effect was not due to an underestimation of the time remaining, as was demonstrated in Experiment 4.

Table 2
Moment of Maximal Closing Velocity of the Hand (V), Averaged Over 10 Subjects, for Each Combination of Time-to-Contact (t_c; in Milliseconds) and Angle of Approach

	Angle of approach											
	−2°		−1°		0°		1°		2°		Mean	
t_c	*V*	*SD*	*V*	*SD*	*V*	*SD*	*V*	*SD*	*V*	*SD*	*V*	*SD*
823	1,717	149	1,757	152	1,683	95	1,699	84	1,705	139	1,712	124
523	1,668	80	1,682	56	1,660	57	1,639	54	1,664	55	1,663	60
223	1,650	44	1,665	37	1,665	49	1,673	52	1,674	65	1,665	49
Mean	1,678	101	1,701	101	1,669	68	1,670	67	1,681	92		

Note. The balls passed the subject at 1,623 ms.

A possible explanation of the results reported thus far is that in interceptive actions subjects do not really predict passing distance, but use a more continuously adapting strategy. The last experiment was carried out to examine this possibility. Analysis of the movement trajectories of the hand in catching actions was thought to reveal whether predictive information about the required future position is used in order to coordinate the action. If the subjects rely on such information, the movement trajectories will not be different for balls that pass at the same distance, but approach at slightly different angles. If, however, the action is geared to information relating to the instantaneous sideward distance of the ball, we expect that different angles of approach will affect the movement pattern of the hand. To test this hypothesis, we asked subjects to catch balls as the complete ball flight was visible. The angle at which the balls approached was manipulated.

Method

Subjects. Five subjects (4 men, 1 woman) volunteered to participate (mean age = 27.6 years; range = 25–30). All reported normal or corrected-to-normal vision.

Experimental set-up. The set-up used was identical to the one described in Experiment 4. Only two changes were made: The subject did not wear the LCD glasses, and only the five balls approaching the same passing distance were used.

Procedure. The subject was instructed to catch the approaching ball with the right hand, by moving the hand along the horizontal bar. The total flight trajectory was visible. The subject was standing at a designated point, holding the hand at a specified position. Two blocks of trials were presented in which the passing distance was either 55 cm ("close") or 75 cm ("far") to the right of the initial hand position; these were semicounterbalanced over the subjects. The different passing distances were made possible simply by changing the position of the subject. During each block of trials all five balls were presented five times each, in a randomized order. The rare trials in which the subject did not catch the ball were repeated. Only the registrations of successful catches were saved. Running the experiment took about 30 min/subject.

Results

From the filtered (10-Hz, recursive second-order Butterworth filter) MILCU data (hand position as a function of time) and the optoreflector data (used to determine the moment of catch), the following dependent variables were derived (cf. Figure 9): (a) moment of initiation of the hand movement (T_{ini}), (b) moment of maximal hand velocity ($T_{\text{max vel}}$), (c) position of the hand at the moment of maximal hand velocity ($P_{\text{max vel}}$), (d) magnitude of the maximal hand velocity (V_{max}), (e) magnitude of the hand velocity at the moment of catch (V_{catch}). For each dependent variable a repeated measures ANOVA was performed on the means of the five trials per subject per condition, with the factors angle of approach (5) and passing distance (2). The mean effects of angle of approach and passing distance are presented in Figure 10.

Movement initiation (Figure 10A). The moment of initiation of the hand movement was found to be affected only marginally by the angle of approach, $F(4, 16) = 2.6, p < .08$, whereas passing distance turned out to have a significant main effect, $F(1, 4) = 11.4, p < .05$. The interaction between angle of approach and passing distance was not significant. When the ball would arrive at the further passing distance, subjects initiated their hand movement earlier. A linear regression analysis on the marginal mean effect of angle of approach revealed that the subjects tended to initiate their hand movement earlier if the balls moved inward (positive angle; $T_{\text{ini}} = 637 - 18 \times \text{angle}$; $R^2 = .71$).

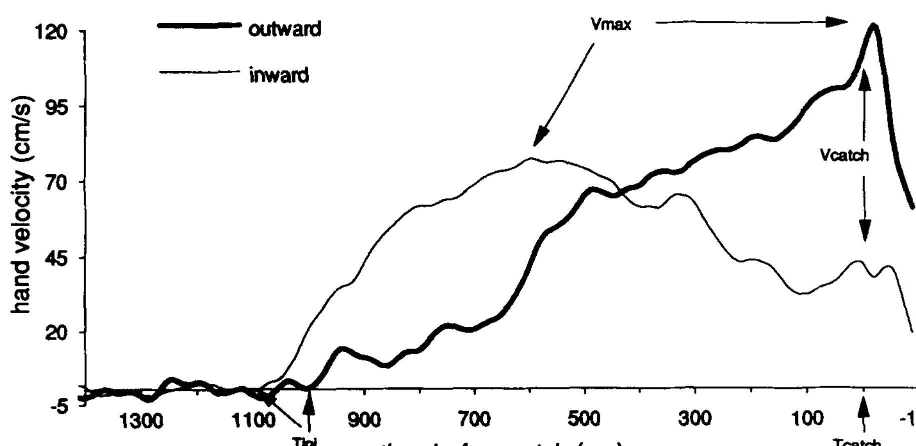

Figure 9. Two typical examples of the sideward velocity of the hand as a function of time. The thin line represents the velocity of the hand catching a ball on the 2° (inward) trajectory. The thick line represents the hand velocity obtained when the ball moved outward (−2°). In both cases the ball passed at 55 cm ("close"). Three dependent variables used in the movement analysis are indicated. (T_{ini} = moment of movement initiation; $V_{\max}$ = maximal hand velocity; V_{catch} = velocity of the hand at the moment of catch.)

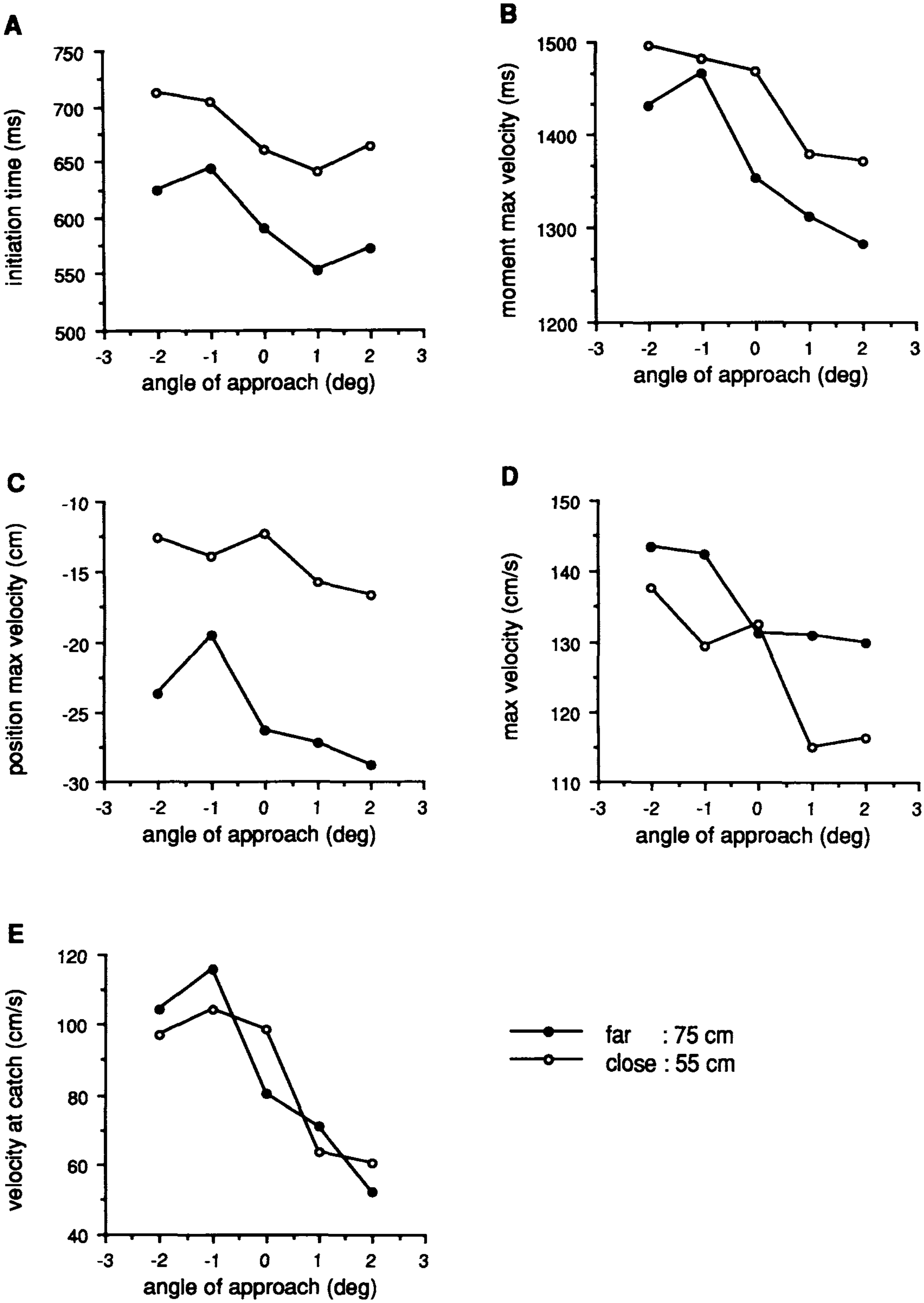

Figure 10. Mean effects of the two factors, angle of approach and passing distance, on the dependent variables moment of movement initiation (A; in milliseconds after ball release; mean *SD* = 84 ms); moment of maximal hand velocity (B; in milliseconds after ball release; mean *SD* = 160 ms); hand position at the moment of maximal hand velocity (C; distance in centimeters from the future passing distance, which was defined as 0 cm; mean *SD* = 10.7 cm); magnitude of the maximal hand velocity (D; mean *SD* = 27.5 cm/s); and magnitude of the hand velocity at the moment of catch (E; mean *SD* = 47.1 cm/s). Deg = degree.

Moment of maximal hand velocity (Figure 10B). The time after release of the ball at which the maximal hand velocity was attained was found to be significantly affected by the angle of approach, $F(4, 16) = 5.4$, $p < .01$, whereas passing distance did not influence this variable. The interaction between angle of approach and passing distance did not show a significant effect, either. A linear regression analysis on the mean effect of angle of approach revealed that the maximal velocity was attained earlier for inward moving balls ($T_{\max\ vel} = 1{,}404 - 40.5 \times \text{angle}$; $R^2 = .91$).

Hand position at the moment of maximal velocity (Figure 10C). The position of the hand at which maximal hand velocity was attained was found to be independent of the angle of approach, whereas passing distance had a significant main effect, $F(1, 4) = 25.4$, $p < .01$. No interaction effect was observed. Inspection of Figure 10C reveals that maximal hand velocity occurred at a larger distance from the future passing point if the ball passed at a larger distance.

Maximal hand velocity (Figure 10D). The main effect of angle of approach on maximal velocity tended toward significance, $F(4, 16) = 2.7$, $p < .07$. Passing distance did not affect this variable and the interaction was also nonsignificant. A linear regression analysis on the marginal effect of angle of approach, averaged over the subjects, demonstrated that maximal velocity was smaller if the balls were moving inward ($V_{\max} = 131 - 5 \times \text{angle}$; $R^2 = .95$).

Hand velocity at the moment of catch (Figure 10E). The velocity of the hand at the moment of catch turned out to be significantly affected by the angle of approach, $F(4, 16) = 24.8$, $p < .001$, whereas the main effect of passing distance was nonsignificant. The Angle of Approach × Passing Distance interaction, however, was significant, $F(4, 16) = 3.1$, $p < .05$. Linear regression analyses on the mean effect of angle of approach performed for each passing distance separately revealed that the hand velocity at the moment of catch was smaller for the inward moving balls and that this effect was stronger for the further passing distance. For the close condition, the best fit line was described by $V_{catch} = 84 - 12 \times \text{angle}$ ($R^2 = .74$) and for the far condition by $V_{catch} = 85 - 15 \times \text{angle}$ ($R^2 = .84$).

Discussion

All in all, it is clear that, notwithstanding the fact that in all trials analyzed the subject actually caught the ball, the movement patterns produced varied considerably for the different angles of approach, even though they led to the same final position. Hence, it must be concluded that the subjects did not first estimate future passing distance, and then programmed their movement response.

The movement characteristics obtained seem to be related to the momentary sideward distance of the ball. For outward moving balls the sideward distance was smaller initially and then increased, which was reflected in the fact that the hand movement was initiated later, maximal velocity was higher and observed later, and the velocity at the moment of catch was higher. For inward moving balls the reverse was true (see Figure 9). These findings suggested that the movements were continuously tuned to the information about instantaneous sideward distance of the ball.

If subjects do not move their hands to an estimated future passing distance but rather continuously guide their hand movement on the basis of a source of momentary perceptual information, a possible way to coordinate this movement is to regulate the sideward velocity of the hand on the basis of the distance between the instantaneous sideward position of the ball (X_b) and the current position of the hand (X_h), and the time remaining until the ball breaks the plane of hand movement. The position of the ball is specified by $x/r \times R$ and time-to-contact by the optical quantity τ. The movement velocity required to be at the correct position at the moment the ball passes is specified by the relation

$$\dot{X}_h = \frac{X_b - X_h}{\tau}. \tag{13}$$

The right-hand side of Equation 13 represents an intermodal information quantity that is perceptually available: X_b (in units of ball size) and τ are optically specified, whereas kinesthetic information specifies X_h (which may be supplemented by optical information if the hand is in sight). Note that, since the movement starts with a zero velocity it is impossible to regulate the hand velocity correctly right from the start.

A computer simulation of the ball's motion provided momentary sideward ball positions during the approach (X_bs), which were used to investigate this explanation. Inspection of the data revealed that in 98% of the trials the subjects succeeded in establishing the suggested relation between the perceptually available momentary information and their movement velocity. Figure 11 represents a typical

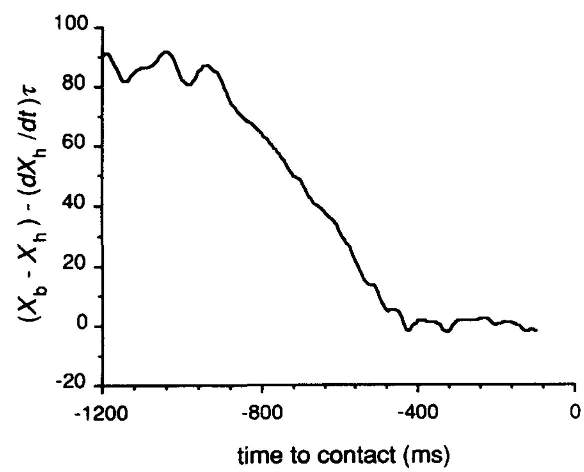

Figure 11. The difference between distance to be traveled ($X_b - X_h$) and the distance that will be traveled ($[dX_h/dt] \times \tau$) as a function of time-to-contact, as obtained for a typical trial. The ball approached at an angle of 1°. Beginning at about 450 ms before the ball passed, the movement velocity was adjusted in such a way that the correct distance would be traveled within the remaining time.

example, which shows that some 450 ms before contact the difference between $X_b - X_h$ and $\dot{X}_h \times \tau$ stabilized around 0 cm. Hence, from this moment onward the difference between the distance to be traveled ($X_b - X_h$) and the distance that would be traveled ($\dot{X}_h \times \tau$) was 0. In other words, this strategy ensured that the hand would be at the right place in the right time. It is important to realize that in order to maintain this constant relation, movement velocity had to be adjusted all the way through, because the distance to be traveled and the time remaining to accomplish this were changing at different rates.

The initial hand velocity was zero, and so it could be predicted that the relationship expressed in Equation 13 could be established earlier if the initially required hand velocity was lower. This required velocity was initially lower for the outward moving balls. Hence, angle of approach may be expected to have influenced the moment at which the hand velocity met the requirements. A repeated measures ANOVA with the factors passing distance (2) and angle of approach (5) on the time before contact (t_c) at which this relationship was established, revealed a significant effect of angle of approach, $F(4, 16) = 3.3, p < .05$. No other significant effects were found to exist. Over the range of angles from outward to inward motion, it appeared to be established later (t_c was smaller; for −2° to 2°: t_c is 408 ms, 363 ms, 379 ms, 355 ms, and 302 ms). This effect reflected the fact that for outward motion the initial required velocity was lower, so that the requirement could be met earlier (larger t_c).

In addition to the moment (and, thus, the time remaining) at which the velocity relationship specified in Equation 13 was established, the distance to be traveled at this moment was examined. A similar ANOVA on the sideward distance between the ball and the hand ($X_b - X_h$) at this moment showed a significant effect for the factor Passing Distance, $F(1, 4) = 16.0, p < .02$. If the ball passed at a larger distance the required velocity was obtained at a larger difference in sideward distance (far: 39.3 cm; close: 32.1 cm).

These two results fit in with the hypothesis that the movement of the hand was regulated continuously on the basis of the information described in Equation 13.

If in the catching action the hand velocity was indeed regulated on the basis of the information presented in Equation 13, the movement characteristics would be captured in computer simulations based on this relationship. To this end, the hand movement velocity was simulated on the basis of the simple model:

$$\dot{X}_h = \alpha(t)\frac{X_b - X_h}{\tau},$$

where $\alpha(t)$ is an activation function, specified by

$$\alpha(t) = \frac{t^n}{\beta^n + \delta * t^n} A$$

for $t \geq 0$, where A is the amplitude of the activation (cf. Bullock & Grossberg, 1988).[13] For a faster than linear activation function (e.g., $\beta = 1$, $\delta = 0$, $n = 1.4$, and $A = 0.8$) with incorporation of a perceptuomotor delay (100 ms), the simulations reproduced many of the characteristics observed in the hand movement velocity pattern.

All but one of the effects of angle of approach, discussed above, were qualitatively captured by the simulated movement patterns. In line with the experimentally obtained patterns, the simulated patterns showed, for the range of angles of −2° to 2°, a decrease in the period between ball release and hand movement initiation; a decrease in the period between ball release and the moment of maximal velocity; and a decrease in the hand velocity at the moment of catch. In addition, the position of the hand at the moment the maximal hand velocity was attained was not affected by the angle of approach, as was observed in the experimental data.

With respect to the differences between the far and close conditions, the model indicated that in the far condition movement was initiated earlier, but the difference was not as large as observed in the data. The hand positions at the moment of maximal velocity obtained for both passing distances roughly matched the experimental data, and the effect of passing distance on this variable was captured in the simulations. As in the hand movement patterns obtained from the MILCU data, maximal velocity was reached at the same moment for both conditions in the simulations. However, the simulated maximal velocity turned out to be larger in the far condition, whereas no difference in this respect was observed in the experimental results. In addition, the velocity at the moment of catch was larger in the simulated far condition, whereas in the experimental data no main effect of passing distance was observed. These characteristics, obtained for the simulated hand movements, were all closely related. Earlier initiation in the far condition would result in smaller maximal velocity and smaller velocity at the moment of catch. In other words, if the simulated hand movement is initiated earlier, the other differences between the simulated patterns and the hand movement patterns are likely to decrease or even disappear.

Hence, although the simulated velocity patterns did not exactly fit the experimentally obtained patterns, most movement characteristics, especially those related to the angle of approach effect, were reproduced by the simple model proposed.

General Discussion

Experiments 1 and 2a indicated that ball size was used as a metric in estimating passing distance, at least in situations in which no distance information was available. Size and distance are optically related quantities, and in the absence

[13] This model shows some resemblance with Bullock and Grossberg's (1988) vector-integration-to-endpoint (VITE) model. It is important to note, however, that the VITE model does not incorporate time constraints. Therefore, it cannot account for interceptive actions, where the hand has not only to move to the correct position, but also to accomplish this within a time limit (Beek & Bootsma, 1991).

of other sources of information knowledge about one of the two is required in order to perceive the other. As the size of objects is more often constant than their distance to the observer, scaling to object size seems to be the most reliable solution to this ambiguity. Moreover, the combination of changing-disparity and changing-size information allows, in principle, perception of the absolute width of the moving object (Regan & Beverley, 1979).

The results (especially those of Experiment 5) clearly demonstrated that in catching a ball, humans do not first predict where it can be caught and then move the hand to this position. This is in line with the fact that instead of triggering preprogrammed actions on the basis of some value of an optical variable, actions are continuously geared to this source of information (e.g., Bootsma & Van Wieringen, 1990; Lee et al., 1983; Savelsbergh et al., 1991). Although predictive information about future passing distance is available in principle, it does not seem to be used as such in controlling the catching action. Indeed, reliance on information predicting when the ball will be where forms one possible way of controlling the action prospectively. However, the predictions would have to be almost perfect, thereby requiring a highly sophisticated perceptual system, perhaps also sensitive to higher order information (e.g., acceleration). Continuous coupling between perception and action is not so dependent on such a precise perceptual system, because accuracy is achieved during the unfolding of the act. The robustness of the perception–action system can, therefore, be regarded as the consequence of this continuous coupling.

The results of Experiment 5 illustrate the way the system seems to operate: It is not hunting for perfect predictive information, but for useful information to which the action can be geared. For catching, a source of information that simply specifies distance does not provide this possibility, as the temporal aspect is left out. To regulate one's actions, action-related information is required (cf., e.g., the specification of required vertical impulse in running over irregular terrain [Warren et al., 1986] and the control of backward–forward displacement in catching fly balls [Babler & Dannemiller, 1993; Chapman, 1968; Michaels & Oudejans, 1992; Todd, 1981]). As is suggested by the present results, the sideward arm movement in catching is regulated by gearing the movement velocity to the perceptually specified (in a combination of optical and kinesthetical information) required velocity. This type of information does not specify when to be where, but how to be at the right place in the right time, regardless of where this might be. The value for prospective control, thus, resides in the fact that action regulation on the basis of this source of information guarantees adequate future hand positioning.

Although future passing distance appears not to be estimated in order to coordinate the catching action, our subjects were able to predict it reasonably well if required to do so. However, to this end they did not rely on the available optical information specifying future passing distance, as has to be concluded from the obstinate angle of approach effect. In order to decide whether an approaching object will pass close enough to be caught, a rough estimate of passing distance will be sufficient to be in the "right ball park." It seems likely that Experiments 1–3, in requiring the subjects to estimate future passing distance, addressed a task that did not reflect the way human actors operate in catching. If the precise future passing distance was relatively irrelevant, the subjects may not have been attuned to the available information specifying it.[14] In order to perform the prediction tasks, they might have needed to infer the estimate from information sources to which they were sensitive. Because the movement characteristics of the catching action showed a clear qualitative relation to the angle of approach effect, the estimates could have been inferred, in one way or another, from the perceptual information specifying required velocity. It is possible that the optically specified momentary sideward distance was conservatively extrapolated (thereby leading to the observed angle of approach effect) to obtain a rough estimate of future passing distance.

The information described in Equation 10 did not seem to be used in these estimations. Nevertheless, it might play a role in distinguishing between approaches that will result in a collision with the point of observation, and those that will not. As mentioned before, values of $\dot{x}/\dot{r}$ between −0.5 and 0.5 specify, for all nonaccelerative approaches, that the object is on a collision course with the observer. This is true irrespective of object size and direction of motion, which makes this optical quantity a rather robust source of predictive information.

If the coordination of actions is based on continuous action-related information, rather than on information predicting spatiotemporal aspects of future events, experimental designs that incorporate the estimation of future events have to be regarded with some caution. The studies that demonstrated progressive underestimation of time-to-contact with increasing estimation interval magnitudes typically involved such an estimation (e.g., Cavallo & Laurent, 1988; McLeod & Ross, 1983; Schiff & Detwiler, 1979; Schiff & Oldak, 1990). At various times before the approaching object would have reached the observer, the presentation was terminated and the subject was required to indicate the time until arrival. Bootsma, Marteniuk, and MacKenzie (1991) demonstrated that changes in the time at which a response action had to be initiated progressively decreased the underestimation of time-to-arrival. They concluded that this underestimation may indicate that subjects did not fully focus their attention on the information long before the action needed to be initiated. This assumption suggests that time-to-contact is not simply used as a prediction of the remaining time, but that the accuracy of estimation is related to the action being subserved (cf. Stoffregen & Riccio, 1990).

If, in Experiment 4, the moment of ball passing would have been estimated in order to control the catching action, an underestimation of about 40% (cf. Cavallo & Laurent, 1988; McLeod & Ross, 1983; Schiff & Detwiler, 1979;

[14] Because the subjects appeared not to be attuned to the information quantity $\dot{x}/\dot{r}$, this optical variable, although being task relevant, can be considered nonfunctional (Owen, 1990).

Schiff & Oldak, 1990[15]), leading to the hand closing some 320 ms too early in the early condition (t_c = 823 ms), was to be expected. However, the moment of hand closing was found not to be affected by the time-to-contact manipulation. This result may be related to the results of Bootsma et al. (1991) as the catching action needed to be initiated some time before the ball was actually passing by.

In summary, in intercepting a ball subjects appear not to use a point prediction specifying when and where this can be accomplished. Rather, the catching action turns out to be continuously coupled to instantaneous information. Gearing the velocity of the hand movement to the specified required velocity guarantees that the hand will be at the right place in the right time. Instead of spatiotemporal estimates, continuous action-related information is required in order to control one's actions.

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[15] Schiff and Oldak (1990) demonstrated that in transverse motion time-to-arrival was estimated far more accurately than in head-on approaches (radial motion), although the task (and thus time-to-action-initiation) was the same in both instances. However, this difference in accuracy cannot be taken as direct evidence against the time-to-action-initiation assumption, because it might be related to the different optical information that was available in the two conditions. In transverse motion, the optical changes are approximately linear, whereas the same displacement velocity in a head on approach yields a nonlinear rate of change (Schiff & Oldak, 1990). In addition, as Hills (1980) has rightfully pointed out, optical size changes, due to head-on approach, at larger distances are small, whereas the same displacement in the transverse plane has a much larger effect.

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