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RESEARCH ARTICLE

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# Movement reversals in ball catching

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**Abstract** This study aimed to determine whether the interception of a moving object is achieved by implementing a predictive or a prospective strategy. We examined the kinematics of catching movement in a situation in which the catching hand was constrained to move along a single dimension. In line with predictions based on a prospective strategy, the results obtained indicated that, for the same interception point and the same initial hand position, modification of the spatiotemporal characteristics of the ball's trajectory (via modification of the angle of approach of the ball) gave rise to systematic changes in the kinematics of catching movement. Moreover, the production of movement reversals when the hand was already positioned at the interception point, while in line with the predictions of the prospective strategy formalized by Bootsma et al. (1997), allowed for rejection of a predictive strategy.

**Key words** Prospective control · Perception action coupling · Interceptive tasks · Information

## Introduction

Any action, whether it involves reaching out to pick up a cup of coffee, driving a car along a winding road, or intercepting a moving ball, requires shaping one's movement behaviour to accommodate the future. This requirement has been taken to imply that the future must be predicted to allow for planning of the movement pattern to be produced (e.g. Saxberg 1987; Regan 1997). For catching, the task we examine experimentally here, such a perspective means that the catcher must be able to obtain the future spatiotemporal characteristics of the ball in flight. Given that the temporal accuracy of performance is of the order of milliseconds (Alderson et al. 1974; Bootsma and Van Wieringen 1990), such a scheme implies that the prediction must be extremely precise and thereby leads to the postulation of complex dedicated internal structures (e.g. Bahill and Karnavas 1993; McBeath 1990). However, even if the current position, velocity, and other relevant derivatives of the ball's motion could be assessed adequately and integrated with sufficient knowledge about its (aero)dynamic behaviour, unexpected changes in the flight trajectory would have serious consequences on performance. Thus, a strategy based on the prediction of the future point of contact is not only computationally cumbersome (and therefore prone to error), but also not very robust.

A less taxing and more reliable solution can be achieved via an alternative strategy that implies prospective control. "Prospection" entails establishing and maintaining a relationship that ensures the attainment of success (e.g. Chapman 1968; McLeod and Dienes 1993, 1996; McBeath et al. 1995; Michaels and Oudejans 1992; Todd 1981). Prospective strategies are thus based on a close coupling between information and movement (Kugler and Turvey 1987; Bootsma 1998). The information used continuously informs the actor about the state of his/her relationship with the environment, and, in turn, any movement made modifies the state of that relationship. The circular causality relations between information and movement can be described formally by laws of control, which relate generic kinetic properties of movement to generic kinematic properties of perceptual flow (Warren 1988).

In order to bring the hand to the right place at the right time in a catching task, the current lateral hand-to-ball distance needs to be covered in the (first-order) time remaining until the ball reaches the interception plane (Peper et al. 1994). Thus, the velocity required at each instance for correctly carrying out the interceptive action is equal to the ratio obtained by dividing the distance-to-cover by the (first-order) time-to-contact (Eq. 1; Fig. 1). Because the required velocity cannot be reached instantly, Peper et al. (1994) proposed using an

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activation function similar to that of Bullock and Grossberg (1988).

Bootsma and his colleagues (1997; Bootsma 1998) later revised this initial model, for two important reasons: (1) invoking an “external” activation function is not consistent with the ontological bases of the ecological approach to perception and action, and (2) a kinematic property of the flow is related to a kinematic property of the movement (i.e. the required velocity) rather than to a kinetic property (i.e. acceleration). These two considerations led Bootsma et al. (1997) to propose a model with two differential equations, aimed not only at determining the required velocity (Eq. 1) but also at specifying how the required velocity would be integrated into the movement (Eq. 2). This model is based on a difference between the current velocity and the required velocity in which the subject controls the action by modulating the acceleration of movement (Eq. 2):

$$\dot{X}_{h\ req} = \frac{X_h - X_b}{TC_1(Z)} \tag{1}$$

$$\ddot{X}_h = \alpha \dot{X}_{h\ req} - \beta \dot{X}_h \tag{2}$$

where $\dot{X}_{h\ req}$ is the currently required hand velocity, $X_h$–$X_b$ is the current difference in lateral position between hand and ball, $TC_1(Z)$ is the current (first-order) time remaining until the ball reaches the interception plane (i.e. until distance $Z$ is zero), $\dot{X}_h$ and $\ddot{X}_h$ are the current hand velocity and hand acceleration, respectively, and $\alpha$ and $\beta$ are constants. Although the feasibility of prospective strategies has been experimentally explored (McBeath et al 1995; McLeod and Dienes 1993, 1996; Michaels and Oudejans 1992; Peper et al. 1994), no definite empirical arguments have yet been set forth that allow us to refute the contact-prediction hypothesis. The present study provides a direct test of the contact-prediction versus contact-prospection hypotheses.

We examined the kinematics of catching movements in a situation in which the catching hand was constrained to move along a single dimension. This set-up allowed us to vary the characteristics of the ball’s approach trajectory without affecting the future place and time of interception. Three different angles of approach were combined with three different initial positions of the catching hand, placed to the left, right, or exactly at the future interception point. According to the contact-prediction hypothesis, angle of approach should not influence the kinematics of the catching movement, as all trajectories converge to the same interception point. Moreover, in the condition in which the hand was placed at the future interception point, no movement should occur. According to the contact-prospection hypothesis, on the other hand, within each initial hand position condition the kinematics of the catching movement should vary systematically with the angle of approach. Furthermore, in the condition in which the hand was placed at the future interception point, reversal movements of the hand should be expected (for oblique angles of approach), with the hand initially moving away from the future interception point in a direction determined by the trajectory of the ball before the hand returns to make the catch.

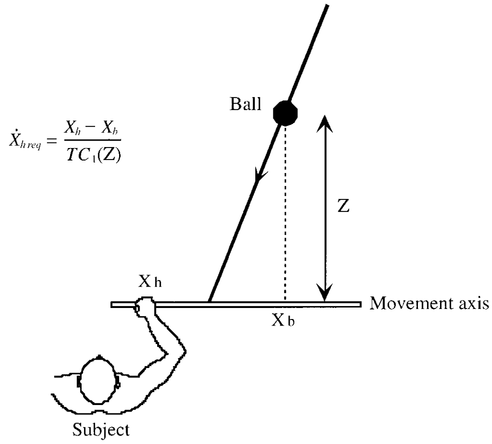


**Fig. 1** Diagram representing the current lateral distance. In Peper et al.’s (1994) strategy, the *subject* must cover the current lateral distance $X_h$–$X_b$ within the (first-order) time remaining until the *ball* reaches the interception point $TC_1(Z)$

## Materials and methods

### Subjects

Nine right-handed male students at the Faculty of Sport Sciences in Marseilles participated in the experiment. They all had normal vision but varied in their experience in ball sports.

### Apparatus

A motor-driven cart, carrying the tennis ball to be caught on a pole extending 35 cm above and 20 cm in front of the cart, could be made to move along a 6-m long track. The first part of the track consisted of a descending ramp to facilitate the launching of the cart. The cart’s velocity stabilized at 2.8 m/s after travelling 2 m. Hidden on the first part of the track by black curtains, the ball was visible during the final 4 m, corresponding to a time of 1.43 s. The whole track could be rotated around an axis that ran through the catching point, thus allowing manipulation of the angle of approach without affecting any other characteristic of the ball’s approach. The position of the cart over time was determined by means of an optical encoder (with a precision after 6 m better than 0.8 cm). In order to catch the ball, subjects could move their arm laterally along a metal guiding bar. Hand movement was measured by means of a telescopic rod attached at one end to a metal ring around the subject’s wrist and the guiding bar and at the other end to a lever potentiometer located on the wall behind the subject (precision ±1 mm). Three microswitches placed on the inside of the guiding bar recorded movement onset. Two switches, one located 4 m before the end of the track and the other at the end, turned the data acquisition device on and off. The latter two switches also controlled the liquid crystal (LCD) spectacles worn by the subjects. The first signal opened the spectacles and the second signal closed them. The signals from the optic encoder, the potentiometer, the three microswitches, and the two switches on the track were detected by means of the Biopac data acquisition system at a sampling frequency of 1 kHz.

### Task and procedure

Subjects wearing the LCD spectacles were to catch the ball with their right hand. The catching movement was constrained to the side-to-side direction by the bar located in front of the subject (Fig. 1) just above the shoulder. Before each trial the subject placed his foot in one of two possible positions and his hand at

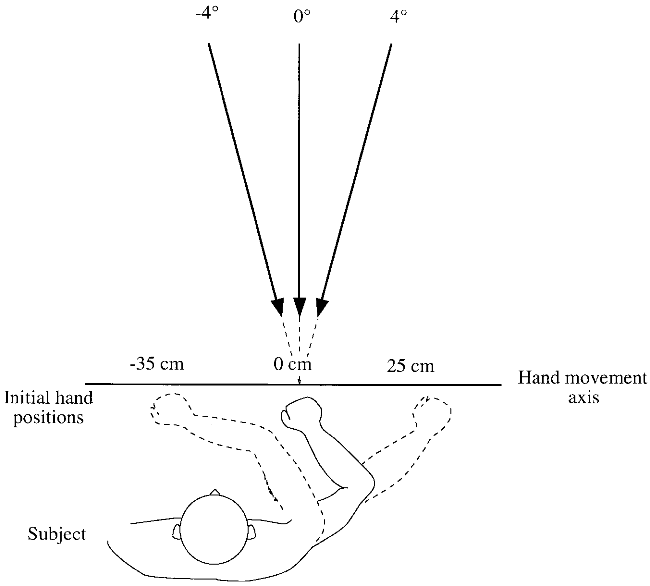


**Fig. 2** Schematic representation of experimental conditions. The current lateral ball-to-hand distance was manipulated by jointly varying the initial hand positions (IHP: –35 cm, 0 cm, and 25 cm) and the ball's angle of approach (–4°, 0°, and 4°)

one of three possible initial positions, as indicated by the experimenter. They were to keep both feet in place until the ball was caught, but were allowed to bend to the side if necessary during a trial. The instructions were to catch the ball and not start moving until the ball became visible. The experimental room was illuminated with ultraviolet ("black") light. Before the experiment and between each trial the spectacles were closed and the subjects were put in an intensely lighted environment (halogen film lamp) to prevent habituation to darkness. Two seconds before the beginning of a trial the halogen lamp was turned off, the experimenter asked the subject whether he was ready, and then the ball appeared in the subject's visual field. During the trials, only the ball and the hand (wearing a white glove) were visible.

Subjects were allowed some practice trials to become familiar with the task and instructions. The practice phase ended when the subject caught five successive balls. The experiment proper consisted of 45 trials. Given that the arrival point of the ball was kept constant to avoid having to calibrate the catching point, the initial posture of the subjects was varied by asking them to place their feet on one of two marks on the floor located 15 cm apart. The inter-trial interval was about one minute, during which data storage was performed, the subjects placed their feet and right hand at the positions indicated by the experimenter, and the ball's approach angle was adjusted.

### Independent variables

We experimentally manipulated the current lateral hand-to-ball distance by changing the ball's angle of approach and the hand's starting position on the guiding bar (Fig. 2). Three initial hand positions were used: IHP1 (–35 cm), IHP2 (0 cm) and IHP3 (25 cm). Three different angles of approach were used: outward (–4°), perpendicular (0°), and inward (4°).

### Data analysis

From the filtered position-time series of the hand (second-order double-pass Butterworth filter with a cut-off frequency of 5 Hz) hand velocity was derived using the first central difference method. Reversal movements were defined as movements that showed a change in direction (i.e. the hand started by moving to the right and then moved to the left, or vice versa). In order to eliminate "parasitic" reversals from the analysis, we retained only those movements in which the direction change was substantial (i.e. velocity peaks greater than 20 cm/s). A reversal was labelled L/R when the hand moved leftward first and then rightward, and R/L when it moved rightward then leftward.

## Results

On all trials the balls were successfully caught by the subjects. The analyses therefore focus on (1) the movement reversals and (2) the kinematics of movement.

### Movement reversals

The percentages of occurrence of movement reversals (i.e. without taking the direction of the reversal into account) were analysed first. This was followed by analysis of type L/R reversals and then type R/L reversals (Fig. 3).

#### *Percentage reversals*

An analysis of variance with repeated measures of the angle of approach and initial hand position revealed a significant main effect of initial hand position ($F_{(2,16)}$=17.621, $P$<0.001) and a significant interaction between the angle of approach and the initial hand position ($F_{(4,32)}$=3.384, $P$<0.05). *A posteriori* comparisons (Newman-Keuls) between the different starting positions showed that for IHP2 (0 cm), the reversal rate was higher than for IHP1 (–35 cm) and IHP3 (25 cm) (50%, 6%, and 11%, respectively). The interaction between the angle of approach and the initial hand position (Fig. 4) in-

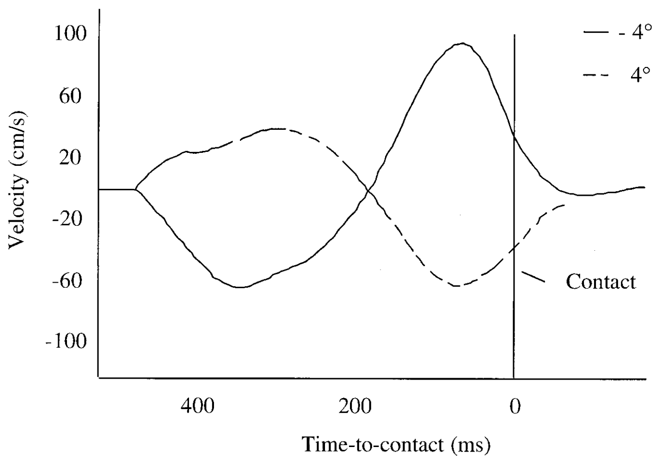


**Fig. 3** Velocity curves illustrating reversal movements obtained when the initial hand position coincided with the ball's future landing point. The outward angle of approach (–4°) gave rise to an L/R reversal whereas the inward angle (4°) gave rise to an R/L reversal

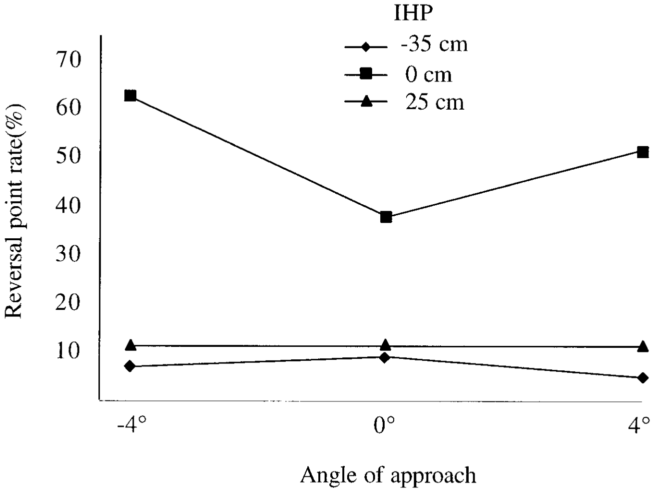


**Fig. 4** Effect of angle-of-approach and initial-hand-position (*IHP*) on the reversal rate. The angle of approach had no impact on the reversal rate in the conditions where the hand was 25 cm (*IHP*3) or –35 cm (*IHP*1) from the interception point. In condition *IHP*2 (0 cm) the angle of approach did affect the reversal rate. Reversal points on outward (–4°) and inward (4°) approaches outnumbered those on perpendicular approaches (0°)

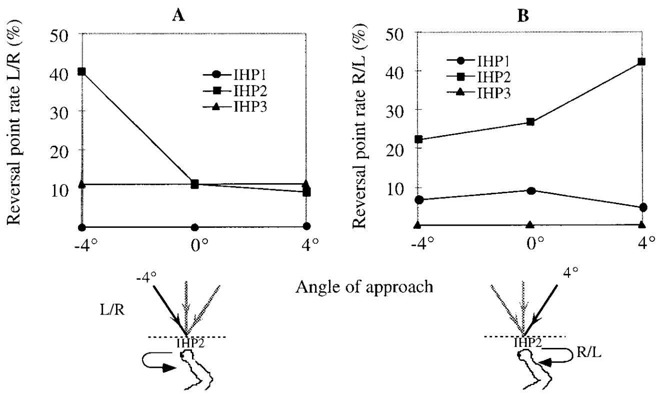


**Fig. 5.** Effect of angle of approach and initial hand position on the two types of reversal point rates: L/R (**A**) and R/L (**B**). **A** Reversals in condition *IHP2* (0 cm) outnumbered those in conditions *IHP1* (–35 cm) and *IHP3* (25 cm). In addition, the angle of approach had no effect on the reversal point rate in condition *IHP1* or *IHP3*, whereas in condition *IHP2* it did. There were more reversal points for outward (–4°) than for perpendicular or inward angles (0° and 4°). (B) There were more reversals in condition *IHP2* (0 cm) than in conditions *IHP1* (–35 cm) and *IHP3* (25 cm). Although the interaction was not significant, in condition *IHP2* (0 cm) the subjects tended to produce more reversal points for an inward angle of approach (4°) than for a perpendicular (0°) or outward one (–4°)

dicated that the angle of approach had no impact on the number of reversals for IHP1 and IHP3, whereas it did for IHP2 ($P<0.05$). In condition IHP2 there were fewer ($P<0.05$) movement reversals for a perpendicular approach (0°) than for outward (–4°) or inward (4°) approaches (37%, 62%, and 51%, respectively).

*L/R reversals*

The initial hand position, the angle of approach, and the interaction between these two factors all had significant effects, ($F_{(2,16)}=5.741$, $P<0.05$, $F_{(2,16)}=7.871$, $P<0.01$) and ($F_{(4,32)}=10.062$, $P<0.001$), respectively. *A posteriori* comparisons showed that subjects demonstrated more L/R reversals (i) in condition IHP2 (0 cm) than in conditions IHP1 (–35 cm) and IHP3 (25 cm) (20%, 0%, and 11%, respectively), and (ii) for an outward angle of approach than for a perpendicular or inward one (17%, 7%, and 6%, respectively). The angle-of-approach by initial-hand-position interaction showed that the angle of approach had no effect on the number of L/R reversals in conditions IHP1 and IHP3, while having an impact in condition IHP2 (Fig. 5 A). More reversals were obtained for outward angles of approach than for perpendicular and inward ones (40%, 11%, and 8%, respectively).

*R/L reversals*

Only the initial hand position had a significant effect on the R/L reversal rate ($F_{(2,16)}=7.633$, $P<0.05$). The angle-of-approach main effect and the angle-of-approach by initial-hand-position interaction were not significant: ($F_{(2,16)}=1.338$ and $F_{(4,32)}=1.957$). *A posteriori* comparisons between the different starting positions showed that for IHP2 (0 cm), the number of R/L reversals was higher than for IHP1 (–35 cm) and IHP3 (25 cm) (30%, 6%, and 0%, respectively). For IHP2, changing the angle had a marginally significant effect ($P<0.10$) on the number of reversals produced [22% for an outward angle (–4°), 26% for a perpendicular angle (0°), and 42% for an inward angle (4°)] (Fig. 5B).

Implementing a predictive strategy implies the actor has advance knowledge of the spatiotemporal characteristics of the interception point. Based on this type of strategy, in condition IHP2 where the hand was already located at the future interception point, no movement should occur. Our analyses showed, however, that under this condition movement reversals appeared in 50% of the trials. One can nevertheless wonder whether these reversals were functional. In other words, does the production of movement reversals necessarily reveal the use of a prospective strategy? The foregoing results pointed out that reversal production exhibited a number of constant features. When the subject's hand was placed at the future interception point, both the number and the type of reversals varied as a function of the angle of approach. In line with Bootsma et al.'s (1997) strategy, the number of reversals was higher for inward (4°) and outward (–4°) approach trajectories than for those perpendicular to the hand-movement axis (0°). Moreover, the number of L/R reversals was higher for outward ball trajectories, whereas for inward trajectories it was the number of R/L reversals that tended to be higher. Thus, the movement reversals produced did not correspond to random movement sequences generated as the subject made

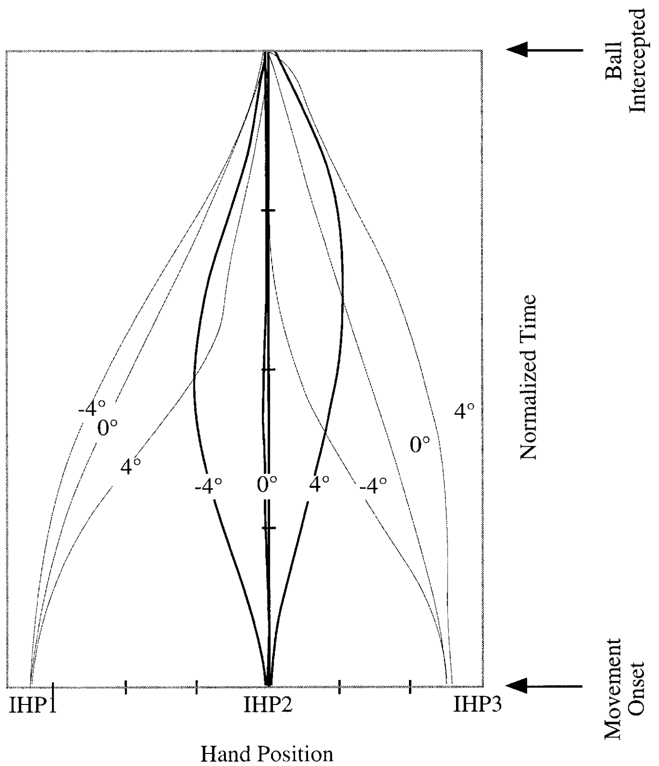


**Fig. 6** Time course of hand movement (normalized from movement onset to interception) for an exemplary participant catching balls from different initial hand positions (*IHP1* –35 cm, *IHP2* 0 cm, *IHP3* 25 cm) as the ball travelled towards the interception point at different angles (–4°, 0°, 4°). Each experimental condition gave rise to different hand kinematics

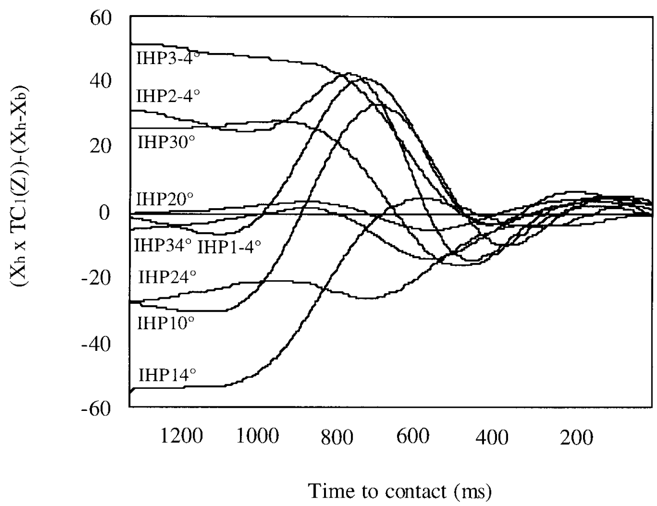


**Fig. 7** Time course of the algorithm $(\dot{X}_h \times TC_1(Z))-(X_h-X_b)$ during a trial performed by the same subject in the nine experimental conditions. The relation stabilized around the zero point an average of 300 ms before contact in all conditions: IHP1 (–35 cm), IHP2 (0 cm), and IHP3 (25 cm)

approximations in estimating the future arrival point of the moving ball. Instead, the reversals depended on the state of the subject–environment relationship.

## Unfolding of the action

The number and type of movement reversals observed thus clearly contradicts the contact-prediction hypothesis. Further support for the contact-prospection hypothesis is to be found in the kinematics of movement, in other words in the way in which the action unfolds over time. In this respect, a first important result to note is that, in accordance with a prospective strategy and corroborating the findings of Peper et al. (1994), we systematically obtained different kinematic response curves for each experimental condition, that is, for all combinations of the angle-of-approach and initial-hand-position factors (Fig. 6). Thus, the kinematics of movements starting from the same initial hand position differed as a function of the angle of approach, notwithstanding the fact that all trajectories converged toward the same interception point.

According to the strategy proposed by Bootsma et al. (1997) these different kinematic patterns are exactly what should be expected from the operation under varying initial conditions of a single law of control. The model (summarized in Equations 1 and 2) predicts that, as the time remaining decreases, the hand velocity matches the required velocity more and more, with the exact time course determined by the model parameters $\alpha$ and $\beta$. Thus, the model predicts that as time remaining runs out the distance that will be covered in the time remaining $TC_1(Z)$ by the current velocity $\dot{X}_h$ converges toward the current distance to be covered $X_h-X_b$. In other words, the difference between $\dot{X}_h \times TC_1(Z)$ and $X_h-X_b$ approaches zero when the ball is about to cross the hand-movement axis. Because the need to implement large changes in short time delays would jeopardize the robustness of the prospective strategy, one should expect the difference to become close to zero some time before the moment of contact.

The results obtained, illustrated in Fig. 7, show that this relation indeed stabilized around zero when the time-to-contact was approximately 300 ms, regardless of the particulars of the experimental condition. The initial portion of the curves corresponds to the time needed by the actor in each case to initiate the catching movement and reach the required velocity. Note that the unfolding of the action follows the same logic for the situations in which the initial hand position coincided with the ball's future arrival point (and movement reversals were produced). The stabilization of the relation around the zero point approximately 300 ms before contact means that at that point the current hand velocity was equal to the required velocity. This allowed the actor to reach the point of contact at the same time as the moving ball.

# Discussion

The aim of this study was to determine whether the interception of a moving object is achieved by implementing a predictive (e.g. Bahill and Karnavas 1993; Regan

1997; Saxberg 1987) or a prospective (e.g., Bootsma et al. 1997) strategy. The underlying principle of the contact-prediction hypothesis is that movement production demands specification of the extent and duration of the movement to be made. It thus separates perception and action, with the first merely serving to provide the spatiotemporal requirements for the second. Under the contact-prospection hypothesis, perception and action are considered to be mutually dependent, with information about the current state of affairs being continuously (although perhaps with a delay) integrated into the movement. The characteristics of the ongoing movement are thus part of the information used to guide it.

In line with predictions based on a prospective strategy, the results obtained here indicated that for the same interception point and the same initial hand position, modification of the spatiotemporal characteristics of the ball's trajectory gave rise to systematic changes in the kinematics of the catching movement. Analyses showed that the prospective strategy proposed by Bootsma et al. (1997) accounts well for the kinematic results obtained. It is interesting to note that our procedure could have been expected to favour the contact-prediction hypothesis. Indeed, notwithstanding the fact that the position for the feet was randomly varied, all balls were intercepted at the same absolute position in space. Nevertheless, the data are not consistent with a contact-prediction hypothesis.

The movement reversals observed in the present context are reminiscent of the movement reversals observed by Bizzi et al. (1984) in the pointing behaviour of deafferented monkeys. The latter study clearly demonstrated that movement arises from a gradual shift in the equilibrium point from the initial hand position to the target position, rather than being instantly placed at the target position. In the same way, the present findings demonstrate that movement in catching tasks should be understood as being continuously regulated on the basis of a prospective strategy, rather than being instantly directed towards the future interception point.

Some of the present results nevertheless call for comment. In cases where the initial hand position coincided with the ball's future arrival point, one can wonder why the inward and outward angles of approach did not always lead to movement reversals. In the same line of thinking, when the angle of approach was perpendicular to the hand-movement axis (in which case, for the strategy tested here, the actor should not be expected to move at all), why were movement reversals nevertheless observed on one-third of the trials? One possible explanation for these results might lie in the very nature of the strategy being tested. Warren (1988) stressed that prospective strategies are not deterministic in that they do not prescribe behaviour. On the contrary, they can be applied in different ways (observable as variations in model parameters), depending on the actor's intentions. This may have been all the more true in our experiment where the spatiotemporal constraints inherent in the task performed were not extremely demanding. Further research is needed to test the strategy in more highly constrained situations.

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