Hitting moving targets: Co-operative control of 'when' and 'where'

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Abstract

In this study we present evidence that two independent regulatory mechanisms, governing when and where the target will be hit, function together to allow us to hit moving targets. In the first part of the paper we show that subjects anticipate that the targets will have moved by the time they reach them, but that they do not anticipate how far they will have moved. The resulting systematic errors are largely made up for by continuously adjusting the movement of the hand as the estimate of the position at which the target will be hit improves. The estimate improves during the movement because the time for which motion is predicted, rather than perceived, decreases as we get closer to the moment of the hit. In the second part we argue that part of the errors cannot be accounted for by continuously adjusting the movement of the hand, due to the time it takes for visual information to be transformed into muscle contractions. These errors are compensated for by moving the hand more quickly towards fast targets.

PsycINFO classification: 2330

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1. Introduction

Hitting a target takes time. It takes several hundred ms to initiate a movement (the reaction time), and another few hundred ms for the hand to reach the target

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(the movement time). If the target is moving, its position will change during this time. In order to account for this change in position, one could predict the remaining displacement on the basis of the target's velocity and the remaining time to impact. However, people do not appear to do so. We found that a moving background that changes a target's perceived speed, does not change the hand's trajectory when hitting it (Brenner and Smeets, 1994a; Smeets and Brenner, 1995a). Moreover, trajectories towards moving targets differed systematically from those towards static targets that subjects hit at the same position (Brenner and Smeets, 1994a; Smeets and Brenner, 1995a). It appears that the movement of the hand is continuously adjusted in response to the changing visual information on the target's position.

Several findings suggest that motion of the hand is indeed under continuous visual control. Bootsma and Van Wieringen (1990) found that the variability in the direction of motion of professional table-tennis players' bats during attacking forehand drives decreased as they approached the moment of contact with the ball. Lee et al. (1983) demonstrated that movements of the arm and leg when jumping to hit an accelerating ball are geared to the rate of optical expansion. Pélisson et al. (1986), and Prablanc and Martin (1992), showed that subjects adjust the movements of their hand when the visual target towards which they are moving is displaced, even if the displacement itself is not detected. However, although continuous visual control can improve performance, it is no guarantee for hitting the target. It takes about 110 ms for visual information to influence the movement of the human hand (Smeets and Brenner, 1995b; Prablanc and Martin, 1992), during which time the target will have moved on.

To our knowledge, there have only been two attempts to model the way in which continuous visual control can enable us to intercept moving targets. Peper et al. (1994) suggested that lateral motion of the hand is guided by the instantaneous lateral distance between the target and the hand (note that the actual equation they present requires that kinaesthetic information on the lateral position of the hand be available in units of target size, which is not very likely). In contrast, we proposed that lateral motion of the hand is guided by the instantaneous lateral distance between the hand and a constantly changing estimate of where the target will be hit (Smeets and Brenner, 1995a). In the first part of this paper we present evidence that subjects use such an estimate (although we do not propose that subjects are aware of doing so), and show that this estimate is independent of the target's velocity.

Our model (Smeets and Brenner, 1995a) failed to explain one striking aspect of performance in the experiments. The model could accurately reproduce the differences between the trajectories of the hand towards static targets at different

positions, and towards targets moving at different velocities. However, despite explicit instructions to hit the targets as quickly as possible, subjects hit fast targets more quickly than they did slow ones. Our model provides no reason why this should be so. This tendency to move faster towards fast targets was also found when subjects were asked to intercept (Van Donkelaar et al., 1992) or grasp (Chieffi et al., 1992) targets as quickly as possible. Thus, the change in velocity presumably helps us perform the task. According to our model, the error in the estimate of where the target will be hit decreases during the movement. Until now, we have ignored the time it takes for new visual information to influence the movement of the hand. In the second part of this paper we propose that the speed with which the hand is moved varies in order to compensate for the error that remains at the last moment at which visual information can influence the hand (i.e. 110 ms before impact).

The proposed mechanism for hitting moving targets was first presented at the joint meeting of the Dutch Physiological Society and The Physiological Society, Nijmegen, 10–11 June 1994 (Brenner and Smeets, 1994b).

2. Methods

The data presented in this paper are the result of additional analysis of the data of an experiment that has already been published (Brenner and Smeets, 1994a; Smeets and Brenner, 1995a). For a detailed description of the equipment and experimental protocol see Smeets and Brenner (1995a). In short, subjects were asked to hit moving (or stationary) targets as fast as they could with a cylindrical rod (2 cm diameter; 22.5 cm long). The target was a 'spider' that walked across a background of randomly oriented lines (on a frontal screen in a dark room). Subjects started with the tip of the rod near a specified position about 40 cm from the screen. The moving targets appeared 8 cm to the left (and about 40 cm in front) of the tip of the rod, moving rightward at a constant velocity of 6, 9, 12, 15, or 18 cm/s. The static targets were exactly in front of the rod, or 3 cm to the left or right. There were four additional conditions in which the background of randomly oriented lines moved to the left or to the right at 6 cm/s. The target moved at 6 or 12 cm/s when the background moved to the left, and at 12 or 18 cm/s when it moved to the right. Subjects were given several practice trials to get accustomed to the set-up, after which they were each presented with 192 targets to hit. Subjects never knew what the next stimulus would be. We collected a full set of data for 12 subjects (including the authors).

3. Part 1: Aiming ahead of the target

The direction in which the hand moves does not provide direct information on the position towards which it is moving, because the hand does not move along a straight line (not even when moving towards static targets; Fig. 1a). As the hand always started at approximately the same position, however, differences in the initial direction of motion must have been due to differences in the visual information that was controlling the movements. A relationship between target position, and the initial direction of hand movement, can be determined from the trajectories towards static targets (in which case we assume that we know which target position was controlling the hand). If we can find a reliable relationship between target position and initial direction of hand movement for the static targets, we can use this relationship to determine a hypothetical 'target position' that would account for the hand's movement when moving towards moving targets.

Figs. 1 and 2 show how this is done. The direction in which the hand was moving was determined 70 ms after it started doing so (a compromise between the wish to determine the direction as early as possible, and the reliability of the determined direction of motion increasing with the velocity of the hand). As a measure of the direction we used the position at which the tangent to the trajectory (dashed line in Fig. 1a) intersects the screen (top border of Fig. 1a). Actually, we did not determine the tangent for the average trajectory at the average position, 70 ms after the hand started moving (as suggested by Fig. 1), but determined the intersection for individual traces, and then averaged the intersections. The circles in Fig. 2 show the thus obtained values (extrapolated movement of rod) for the three static targets.

The thin line in Fig. 2 is a fit to the three circles. This line represents the relationship between the target position controlling the hand's movement (the actual target position for static targets) and the direction in which the hand started to move. Whenever we found a reliable linear relationship (an R^2 of at least 0.9), we used this relationship to determine the hypothetical 'target position' that was controlling the hand's initial movement when hitting the moving targets. We found such a relationship for 9 of the 12 subjects. The other 3 subjects had R^2 values of 0.52, 0.68 and 0.89. The initial movement of the rod towards moving targets was extrapolated in the same way as for static targets (Fig. 1b; intersection of the tangent – dashed line – with the screen). This gives a value for the extrapolated movement of the rod. Following each thick line in Fig. 2a horizontally from this value, until it reaches the thin line, we can estimate the (static) target position for which the hand would be expected to
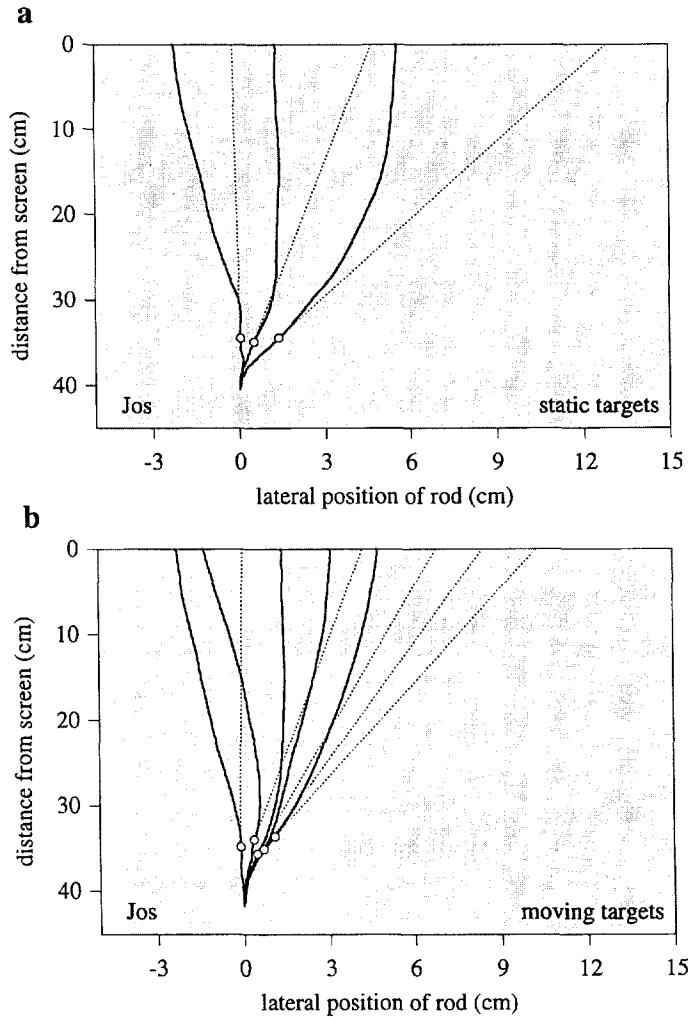
Fig. 1. One subject's average trajectories to the three static (a) and five moving (b) targets. Lateral positions are relative to the initial lateral position of the tip of the rod. The static targets are at − 3, 0 and 3 cm (negative values are to the left; positive values to the right). The other targets appeared at − 8 cm, moving to the right at 6, 9, 12, 15 or 18 cm/s. The circles indicate the average position of the rod 70 ms after it started moving. The dashed lines show the tangent to the trajectory at that moment (actually, the average of the tangents of individual trajectories at the appropriate instants). The movement of the rod is extrapolated along this tangent until it intersects the screen. The intersections are used to determine a hypothetical target position towards which the subject's (Jos) hand is moving (see Fig. 2). Note the difference in scale between the two axes.
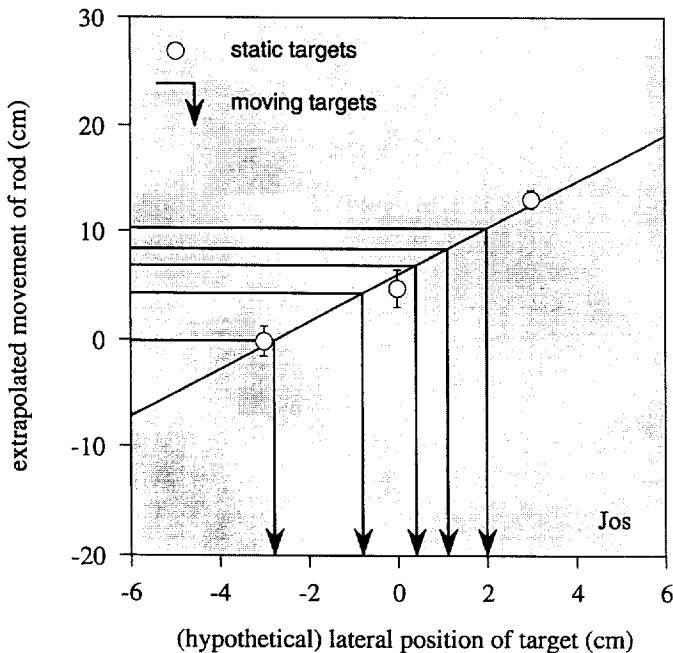
Fig. 2. Determining where the subject (Jos) initially expected to hit the target from the direction in which he moved the rod 70 ms after he started to do so. Circles: the positions at which the tangents to the trajectories to static targets at −3, 0 and 3 cm intersected the screen (extrapolated movement of rod; with standard errors). Thin diagonal line: fit to these three points ($R^2 = 0.98$). Thick lines and arrows: for each target velocity, a hypothetical lateral target position was derived from the position at which the tangent to the trajectory intersected the screen.

start moving the way it did (arrows). This can be considered as the target position that was initially controlling the hand's movements.

If subjects simply move their hand towards the target, the position that was initially controlling the hand's movements, as determined in the manner described above, should coincide with the target's position 110 ms earlier (because of the time it takes for visual information to influence the motion of the hand). If, on the other hand, subjects anticipate where the target will be at some time in the future, the position that initially controls the hand's movements will be further to the right (ahead of the target). If they account for the targets' velocities, the position will be further ahead of the target for faster targets. Fig. 3 shows the position that was initially controlling the hand's movements (expressed as a distance ahead of the target's position 110 ms earlier) for each subject and target velocity. It is evident that subjects use some sort of estimate
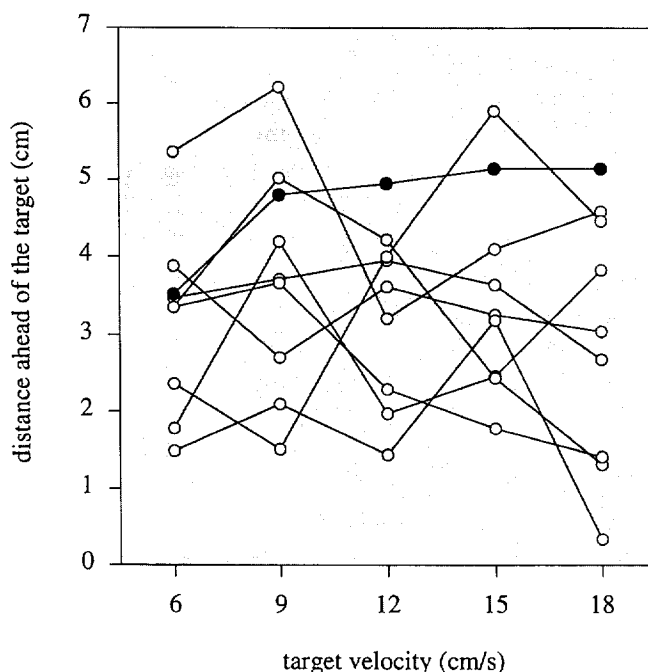
Fig. 3. The hypothetical target position towards which the subjects' hands were moving 70 ms after starting to do so are shown in terms of their distance ahead of the current target position (actually, 110 ms earlier because of the time it takes for visual information to influence the movements of the hand) for each target velocity. The black symbols are the values for the subject of Fig. 1 and Fig. 2 (Jos). Note that all subjects did anticipate that the target would move (values well above zero), but did not account for the target's velocity (the distance ahead of the target did not increase systematically with target velocity).

of where the target will be hit (values well above zero). However, this estimate is independent of the target velocity (Friedman test: 9 subjects; 5 velocities; $p = 0.63$). Subjects appear to start off towards a position a fixed distance ahead of the target.

Fig. 3 only provides information on the initial estimate. It is evident that subjects cannot keep on aiming up to 5 cm ahead of the target. The distance ahead of the target must decrease as the movement progresses. We propose to describe the decrease in the distance ahead of the target in terms of an 'expected velocity' and an 'expected movement time' (again, without wishing to imply that subjects were actually aware of such expectations), so that the distance ahead decreases linearly during the movement. The movement times towards static targets did not depend on their positions (Smeets and Brenner, 1995a). If we assume that this is the 'expected movement time', we can calculate each

subject's 'expected velocity' by dividing their average 'distance ahead' by their average movement time when moving towards static targets (actually, 40 ms longer than the average movement time: the distance ahead was determined from the direction of motion 70 ms after motion onset, which was based on visual information 110 ms earlier). On average, the thus obtained 'expected velocity' was 8.4 cm/s (range: 6 to 12 cm/s).

The use of the same 'expected movement time' for all conditions enables us to attribute a functional role to variations in movement time in the second part of this paper. At this point, however, it is important to note that using the actual movement time instead would not change the conclusion that we use a single 'expected velocity' (the 'expected velocity' that would be obtained by dividing the 'distance ahead' by the actual movement time for each target does not vary systematically with target velocity; Friedman test, $p = 0.63$). Our specific choice for the average movement time towards static targets is rather arbitrary, but fits well with what we will propose in the next section. Other values will obviously result in different expected velocities. However, the 'expected movement time' cannot be too different from the real values, because the predicted target position must be approximately correct when subjects hit the screen. In summary, the present analysis confirms that we do not use the perceived velocity to anticipate where we will hit the target, but that we do anticipate that the target will have moved by the time we reach it. Moreover, it provides us with individual estimates of the 'expected velocity'. The average value found in this manner is close to the 9 cm/s that we postulated when fitting the average trajectories with a simple mass-spring model (Smeets and Brenner, 1995a).

4. Part 2: Why we hit slower targets more gently

In the second part of this paper we examine a possible reason why subjects hit fast targets more quickly than they did slow ones, despite explicit instructions to hit the targets as quickly as possible. Relying on an expected target velocity, rather than on the perceived target velocity, should give rise to systematic errors, because slower targets' velocities are overestimated whereas faster targets' velocities are underestimated. Despite the time it takes to transform visual information on the target's position into the relevant muscle stimulation (*delay*), subjects hit the moving targets quite accurately. The average standard deviation for individual subjects hitting targets moving at the same velocity on different trials is about 1 cm (with only small differences between subjects and target velocities). More importantly, subjects did not tend

to overshoot slow targets and undershoot fast ones. On average, they overshot all targets, even doing slightly more so for the faster targets.

If subjects use the proposed 'expected velocity' (v_e) to predict where they will hit the target, then the predicted final position (x_e) of the target at time t (i.e. the position that is controlling the movement of the hand at that moment) is:

$$x_e(t) = x(t - \text{delay}) + \left(t_e - (t - \text{delay})\right) \times v_e, \tag{1}$$

where t_e is the expected moment of the hit, and $x(t\text{-delay})$ is the target's actual position '*delay*' earlier. For the actual position at the time of the hit (x_a), we can write:

$$x_a(t) = x(t - \text{delay}) + \left(t_a - (t - \text{delay})\right) \times v_a, \tag{2}$$

where t_a is the actual moment of the hit, and v_a is the actual target velocity. In order to hit the target accurately, the predicted position should be equal to the actual position at the moment of the hit (i.e. $x_e(t) = x_a(t)$ for $t = t_a$). This is so if (combining Eqs. (1) and (2)):

$$t_a - t_e = \text{delay} \times (v_e - v_a)/v_e. \tag{3}$$

Thus, one could compensate for a too low expected velocity ($v_e < v_a$) by hitting the target earlier than expected ($t_a < t_e$), and for a too high expected velocity ($v_e > v_a$) by hitting the target later than expected ($t_a > t_e$). Our proposal is that this is the reason that the velocity of the hand depends on the target's velocity.

In order to evaluate the credibility of the proposed link between variations in movement time ($t_a - t_e$), real and expected target velocity, and delay, we examined whether the magnitude of the change in movement time is appropriate. Fig. 4 shows the relationship between the actual change in movement time (with respect to that toward static targets) and the change in movement time that would be required to compensate completely for the systematic error introduced by the delay (the right side of Eq. (3)). In general, the data in Fig. 4 appear to support our proposal. However, 12 of the 45 points deviated significantly from the proposed relationship (t-tests considering the variability in the individual subject's movement times for that condition, in the subject's movement times towards static targets, and in the estimate of the expected velocity – which affects the required change in movement time; $p < 0.05$).

Does this mean we should reject our proposal? We believe not, because subjects were specifically instructed to hit the targets as quickly as possible. This probably reduced the variability in the movement time to some extent. Indeed, the points that deviate significantly from the proposed relationship tend to have smaller actual changes in movement time than required. Moreover, we
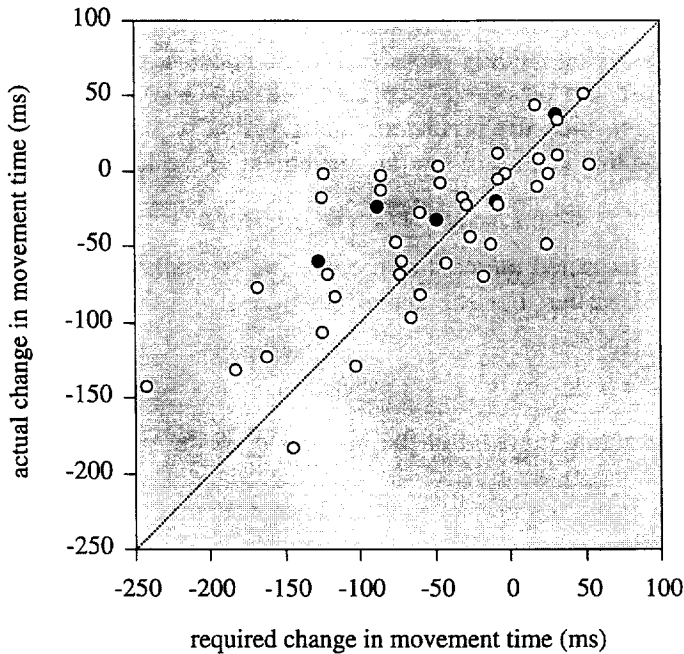
Fig. 4. Comparing the actual changes in movement time (left side of Eq. (3)) with the ones that would be needed to compensate for the difference between the actual and expected velocities during the delay (right side of Eq. (3)). The actual change in movement time is the difference between the subject's average movement time in that condition, and his average movement time for static targets. Positive values indicate that the movement time was longer than for static targets. Negative values indicate that it was shorter. For estimating the required change in movement time we used a delay of 110 ms, and the individual subjects' estimated target velocities. The latter were determined from the average distance ahead of the target (see Fig. 3) and the average movement time towards static targets. The black symbols are the values for the subject of Fig. 1 and Fig. 2 (Jos). The dashed line represents a perfect match between the actual and predicted values.

more or less arbitrarily chose the subject's average movement time toward static targets as the reference for the actual movement times. A slightly different value will shift each subject's data vertically, possibly in some cases into the range of the hypothesis.

Another way to evaluate the credibility of our proposed mechanism for hitting moving targets is by examining the influence of a moving background. Moving the background only influences the target's perceived velocity (Brenner and Smeets, 1994a; Smeets and Brenner, 1995a). Thus, according to our proposal, the moving background should only influence the velocity of the hit. However, changing the velocity of the hit also changes the relationship between the position of the hand and that of the target. Nevertheless, our proposal predicts

how moving the background should influence the position at which subjects hit the targets (on the basis of the change in movement time), so we can compare this with the actual influence of the moving background.

Irrespective of whether the background is moving or not, the difference between the predicted and the actual final position (i.e. the error: Eq. (1) − Eq. (2)) is:

$$x_e(t) - x_a(t) = (t_e - (t - \text{delay})) \times v_e - (t_a - (t - \text{delay})) \times v_a \qquad (4)$$

which, at the moment of the hit ($t = t_a$), becomes:

$$x_e(t_a) - x_a(t_a) = (t_e - t_a + \text{delay}) \times v_e - \text{delay} \times v_a. \qquad (5)$$

Thus, if a moving background only changes the moment of the hit (t_a), its influence on the error will be:

$$\Delta(x_e(t_a) - x_a(t_a)) = \Delta t_a \times v_e. \qquad (6)$$

Fig. 5 shows the actual influence of the moving background as a function of the influence predicted by Eq. (6). Although the data less evidently fall along the dashed line, only one of the 36 points deviated significantly (t-test; $p < 0.05$) from the proposed relationship. The standard errors in the actual influences of the background were about 4 mm; those of the predicted influences where about 2 mm. Thus, although these results are graphically less pleasing than those of Fig. 4, they are completely consistent with the proposed mechanism for hitting moving targets.

5. General discussion

In the first part of the present paper we presented evidence for the use of an estimate of where the target will be hit that is not based on visual information concerning the target's velocity. In the second part we proposed that changes in the velocity of the hit compensate for errors that neglecting the target's velocity introduces in the estimate of where the target will be hit. The proposed mechanism for hitting moving targets can explain why we hit slow targets more gently despite instructions to do so as quickly as possible, and why we do not make systematic errors despite not using the perceived velocity to predict where we will hit the target. One asset of this mechanism is that it simplifies the analysis of the visual information that is required for guiding one's action. Another is that the proposed use of the visual information accounts completely for our reaching the target, so that the only requirement for the mechanical
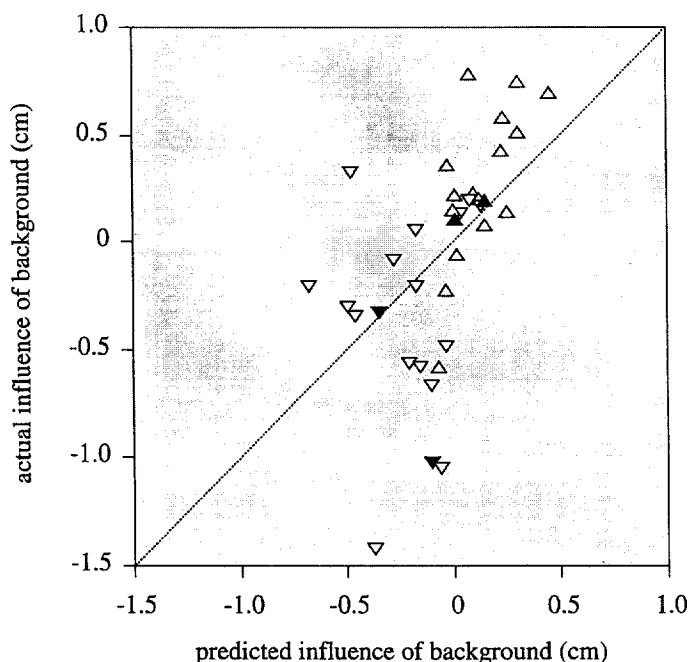
Fig. 5. Influence of moving the background on the position at which subjects hit the screen (relative to the target's position at that moment). The actual influence is the difference between the average positions at which targets (moving at the same velocity) on moving and static backgrounds were hit (left side of Eq. (6)). The predicted influence is the product of the expected target velocity, and the difference between the average movement times for targets on moving and static backgrounds (right side of Eq. (6)). Values are shown separately for background motion in the opposite direction than the target ($\triangle$; target velocities of 6 and 12 cm/s) and in the same direction as the target ($\triangledown$; target velocities of 12 and 18 cm/s). The black symbols are the values for the subject of Fig. 1 and Fig. 2 (Jos). The dashed line represents a perfect match between the actual and predicted values.

parameters (Smeets and Brenner, 1995a) or activation functions (Peper et al., 1994) is that they make the hand reach the indicated position, rather than also having to compensate for errors introduced by the visuo-motor delay. We assume that the predicted final position of the target shifts so slowly, that the last predicted position to influence one's action determines the position that one will hit.

5.1. Independent control

The movement time obviously depends on the acceleration of the hand. In order to determine how quickly to accelerate one's hand (i.e. how much force to exert), according to our proposal all one needs to know is how fast the target is

moving. The target's velocity can be estimated from a combination of retinal and extra-retinal information (Brenner and Van den Berg, 1994). This is probably done during the reaction time, because it was evident from the beginning of the movement that the hand moved at different speeds for different target velocities (Smeets and Brenner, 1995a).

Similarly, in order to determine the position to which we should move our hand, all we need to know is the target's current position and the direction in which it is moving. The position towards which we direct our hand is continuously updated on the basis of the latest perceived target position (again based on a combination of retinal and extra-retinal information), the remaining expected displacement, and the perceived direction of target motion.

Bairstow (1987) and Favilla et al. (1990) present complementary evidence that the speed of the hand is controlled independently of the direction in which it moves. The data presented in the second part of this paper show how these two independent regulatory mechanisms co-operate to help us hit the target. One potential advantage of separating the calculations of when and where to hit the target – only using the perceived velocity to determine 'when' (i.e. how fast to move ones hand) and only the perceived position and direction of motion to determine 'where' – is that it can allow one to do without (implicit) knowledge of the relationships between physical variables (in this case between position, velocity and time). Such knowledge is required if one is to predict where the target will be at some time in the future from its current perceived position and motion. Such knowledge is also often incorporated in variables constructed from diverse sources of potentially accessible information, such as the variable proposed by Peper et al. (1994) to describe the generation of action. The use of such knowledge either requires that the relevant relationships be somehow inherent in the nervous system, or that they be learnt from experience. Moreover it requires combining the output of various 'elementary' detectors. With the proposed independent control, each variable is used separately, allowing each relationship between perception and action (e.g. that between perceived velocity and hand velocity) to be learnt independently. The different variables are only combined in the action itself, so that the combination requires no additional neuronal substrate. A second potential advantage of the proposed mechanism is that only one variable, the perceived position, has to be determined continuously.

5.2. How general is the proposed mechanism?

One clear strength of the proposed mechanism is that it will perform quite well when the motion is not predictable. It seems to be a good strategy for

coping with unpredictable or only loosely predictable target motion, because it combines using expectations based on prior experience with adjusting one's action to the target's position for as long as possible. Using expectations that are based on prior experience can reduce the initial error in the direction in which the hand is moving under any conditions in which the target moves in a systematic manner (if it does not move in a systematic manner, then there is obviously nothing to predict). A problem with the mechanism as proposed in the present paper is that the acceleration of the hand, and thus the movement time, is determined before the hand starts to move. Changes in target velocity while the hand is moving can therefore give rise to considerable errors. Part of the errors will be compensated for by continuous adjustments based on target position. However, it remains to be seen whether the target's initial velocity will continue to determine the velocity of the hand if some other parameter is more predictive of the motion during the last 110 ms.

Subjects usually failed to hit the target during the first few trials (which we discarded as practice trials). We interpreted this as their having to 'set' the values of the expected target velocity and movement time. Of course, the less variability in the target motion and movement time, the better this estimate will be. Evidence from the limits of human competence in sports supports the notion that the level of variability is crucial. Expert table tennis players are distinguished by the consistency of their movement times (Bootsma and Van Wieringen, 1990). Professional cricket batsmen's success in hitting fast balls depends to a large extent on there not being too much variability in the way the ball reaches them (for an extensive discussion of reasons why less predictable balls are harder to hit see Regan, 1992). Performance in table-tennis and cricket is different from that in our study in that motion is not confined to the frontal plane. However, there is no theoretical reason why the proposed mechanism of independent, co-operative control should only be used to hit targets moving in the frontal plane. It remains to be seen whether it is indeed also used for objects moving in other directions.

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