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The quantitative use of velocity information in fast interception

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Abstract We ask whether a target's velocity is considered when planning a fast interceptive action. Human volunteers hit targets that could move at different velocities from across a tilted screen (the hand starting 40 cm away from the screen). We examined how the direction in which the hand initially moved depended on the target's velocity, using various analyses. For slow targets, the initial movement direction was appropriate for the target's velocity. This is evidence that velocity information was used quantitatively in directing the hand. A model analysis showed though that velocity information is probably not used to predict the future target position. For targets moving at a velocity above average, or above 12 cm/s, the initial movement direction did not depend on the target's velocity. Similar behaviour is also known from pursuit eye movements.

Keywords Fast arm movement · Model · Speed · Human · Eye-hand co-ordination

Introduction

In order to intercept (e.g. hit or catch) a moving target, our hand must reach a position at the same time as the target does. To hit a stationary target, one can simply aim for its position. To intercept a moving target, the best strategy would be to aim ahead of it. How far ahead depends on the target's velocity and on how long it will take one to reach it. This makes the interception of moving targets more complicated than the interception of stationary ones. Nevertheless people are remarkably good at dealing with moving targets (e.g. Bootsma and van Wieringen 1990; McLeod and Dienes 1993; Laurent et al. 1994). Apparently, humans have efficient strategies to deal with moving targets. The nature of these strategies is still a point of discussion. It is not clear in what way information about the target's velocity is used to control the movements of the hand. Unfortunately, the distinction between position and velocity—although clear in physical terms—is difficult in terms of psychophysical experiments. The reason for this is that there are considerable lags between a visual event and a possible motor response (such as an arm movement for hitting a target). In the present study, we will focus on the influence of target velocity information on the beginning of hitting movements, a time when the hand's movement direction does not yet depend on its movement history.

Studies in which subjects hit targets that moved across a screen at some distance from the hand have established that subjects do aim ahead of moving targets (van Donkelaar et al. 1992; Smeets and Brenner 1995). This could mean that velocity information is used qualitatively. However, there is some evidence that subjects only distinguish static from moving targets (Smeets and Brenner 1995). Instead of using the perceived velocity, subjects could rely on the velocity of previous targets to control how far ahead of the target they aim (de Lussanet et al. 2001). They could still hit targets moving at various velocities successfully by continuously correcting the hand's movement direction on the basis of the target's changing position (Elliot and Allard 1985; Smeets and Brenner 1995). Thus, instead of using velocity information directly, humans could continuously predict where they would intercept a moving target, using their expectations for the remaining time to interception, and the target's current position. Recently, Brouwer et al. (2002) examined

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where subjects hit targets that disappeared before the subject's hand reached it. With these experiments, Brouwer et al. showed that velocity information is not used to predict where the target will be hit. Sailer et al. (2003) confirmed this result for predictive pointing movements.

However, tasks such as catching need not be controlled by predicting where the target will arrive at a given time. They could be controlled by predicting when the target reaches a certain position (Lee 1976; Rushton and Wann 1999). In this case, the target's velocity should not influence the direction in which the hand moves at all, but only its timing. Another possibility is that people do not plan the place or the time of interception, but that these both emerge from some strategy (McLeod and Dienes 1993; Lenoir et al. 1999; Michaels et al. 2001). If so, we expect to see an influence of target velocity on the initial movement direction, but the magnitude of this influence is difficult to predict because it depends on the strategy. For example, if the subjects' strategy involves scaling the movement velocity with target velocity in order to optimise accuracy (Brenner et al. 2002; Tresilian et al. 2003), the direction of movement will still have to change as well. In more extreme examples in which just one parameter is controlled (e.g. keeping a specific visual quantity constant), very complicated relationships between target velocity and the initial direction of the hand's movement can be expected. A quantitative study of the influence of velocity information can therefore help to distinguish between possible strategies.

It is even possible that an influence of target velocity does not arise from the strategy. For example, the velocity dependence of the reaction time can be attributed to the fact that slower movement takes longer to detect (van Doorn and Koenderink 1982; Tynan and Sekuler 1982; Smeets and Brenner 1994). Target velocity also influences movement velocity and duration (van Donkelaar et al. 1992; Savelsberg et al. 1992; Masson et al. 1995; Carnahan and McFadyen 1996; Fayt et al. 1997; Brenner et al. 1998; Brouwer et al. 2000). This could arise from a control strategy (Brenner et al. 2002), but this has never been proven. Therefore, in examining the use of velocity information it is necessary to allow for such side effects of velocity on the reaction time and the movement time.

Static and moving targets that are hit at the same position have different positions when the hand starts to move. Nevertheless, the direction in which the hand initially moves differs little for such targets (Smeets and Brenner 1995). This demonstrates that people are already aiming ahead of a moving target at the onset of the hand's movement. As we discussed above, this does not necessarily mean that the hand's initial movement direction is suited quantitatively to the target's velocity (Brenner and Smeets 1996). Van Donkelaar et al. (1992) designed an interception task so that targets of different velocities reached approximately the same positions by the time the hand started to move. They compared the results of an experiment in which all targets had the same velocity (predictable) with one in which targets of the various velocities were presented in random order (unpredictable). They found that target velocity had a modest influence on the initial direction of the interceptive movement when the velocity was unpredictable, but a strong influence when it was predictable. This is consistent with the suggestion that the initial movement direction mainly depends on the target's velocity in previous trials, rather than on the current one (de Lussanet et al. 2001). However, people do not always (fully) rely on the velocity of previous targets. This has been shown for example for mildly hemiplegic subjects hitting with their affected arm (van Thiel et al. 2000). As expected, hands' paths were jerky, but the direction in which the hand started was significantly related to the current target's velocity.

Obviously, it would be rather surprising if healthy people cannot use velocity information where hemiplegic ones can. However, it is possible that healthy people under circumstances do not use velocity information, even if they could, for example in order to hit faster. Thus the first question for the present research is whether healthy people do use velocity information when intercepting a target that moves in a fronto-parallel plane. Secondly, is this velocity information used in a quantitative way, and for all possible target velocities? As outlined above, influences of target position and velocity are difficult to separate so we pay special attention to the methodological part, using a qualitative method and a quantitative one. These two analyses are based on the assumption that human subjects use target velocity to predict the target's future position. However, there are data suggesting non-predictive use of target velocity (Brouwer et al. 2002). We previously presented a simple model that uses the target's velocity in such a non-predictive way (de Lussanet et al. 2002b). Therefore we used this model to predict the results of the present experiments (see "General discussion").

We have three reasons to concentrate on the beginning of the movement. Firstly, if subjects already use velocity information when the movement starts, it is very likely that they will use velocity information throughout the movement. Secondly, when the movement starts it does not yet have a history to take into account, so we do not have to make assumptions about what happened earlier in the movement. Finally, this allowed us to develop a method that does not involve perturbations (such as letting the target change velocity or disappear) or illusions (such as a moving background). This is an advantage because such manipulations might change the subjects' strategy. In the experiments, we used targets of different velocities (including zero), which moved from left to right across a screen in front of the subjects. We chose the targets' starting positions so that some targets of different velocities reached the same position around the subject's reaction time while others reached the same position around the time when the screen was hit. Thus, if the current target's velocity is used to predict where the target will be hit, the trajectories towards the targets that are hit at the same position will have the same shape. Alternatively, if target velocity is used to guide the hand, but not to predict where the target will be hit, there will be a quantitative influence of target velocity on the direction of the hand's movement. At the other extreme, if the current target's velocity does not guide the hand at all, the trajectories towards the targets with the same position at the reaction time will start in the same direction, even if the targets differ in velocity.

We designed two methods to analyse the initial movement, one qualitative and one quantitative. Using these measures we will address the question of whether information about the target's velocity has a direct influence on the initial direction of the hitting movement.

The *qualitative method* compares the hand's movement paths in different conditions. This method resembles the one used by van Donkelaar et al. (1992). They compared the paths in sessions in which each target velocity was presented in a separate block of trials with paths in sessions in which the velocities were presented in random order. One drawback of comparing different sessions is that individual subjects display much variability between sessions (de Lussanet et al. 2002a). We therefore made our comparisons with a reference condition within the same session. As in the study of van Donkelaar et al. (1992), we used targets of different velocities that reached the same position by the time the hand started to move. In addition, we included targets of the same velocities, which appeared at different positions (further to the left or right). If the target's velocity influences the hand's movement, the trajectories towards targets that differ in velocity (but not in the position when the hand starts to move) will diverge. The time of this divergence should be the same as the time when trajectories towards targets that only differ in position diverge.

A restriction of the above qualitative method is that it is not suitable for statistical testing, and is sensitive to differences in the subjects' reaction times. Our *quantitative measure* was also based on the divergence in the hand's initial movement direction. The influence of a difference in target velocity was scaled to the effect of a difference in target position to get equivalent values across subjects and sessions. This scaled value (we will call it the "initial adjustment") was used for statistical testing.

General methods

General experimental set-up

This study is part of an ongoing research program that has been approved by the local ethics committee. The 27 subjects were the authors, our colleagues and medical students (20–64 years old; 30% female; two subjects hit with their left hand). Most subjects did not take part in all experiments. Before taking part, subjects were informed about the task and approved of it. Except for the authors though, the subjects were naive with respect to the exact purpose of the experiments. One-third of the subjects were highly experienced with this kind of experiments, and one-third had never taken part in a similar experiment. Subjects sat on an adjustable chair in front of a transparent hitting screen (Macrolon, Lexan) on which the stimuli were presented (Fig. 1). The screen was tilted 30% backwards (top of the screen farther away from the subject) and was fixed in a strong construction so that it could easily withstand a hard blow. The target was a 3D spider animation with a realistic shape, and natural movements. It was presented on a background of randomly oriented 4-cm lines, as if walking on a surface of fir-needles. The targets were hit with the tip of a rod (22 cm long, 2.1 cm diameter) that was held like a pencil between thumb and fingers.

The position of the rod's tip (we will simply speak of "the rod") was recorded at 250 Hz (Optotrak 3010, Northern Digital). The rod's position (i.e. that of its tip) was calculated from the positions of two active infrared markers that were fixed to the long-axis of the rod. In addition, the locations of the subject's eyes were calculated from the positions of another three infrared markers, which were fixed to the stereo shutter spectacles that the subject wore (Brenner et al. 1998).

Stereo images were computed with a graphic workstation (Silicon Graphics, Onyx CMN A011). The alternating left- and right-eye images were presented at 120 Hz (60 Hz per eye) on a monitor behind the screen. To present the alternate images to the appropriate eye only, subjects wore liquid crystal shutter spectacles (StereoGraphics, CrystalEyes 2). Subjects could thus be made to see the stimuli as if they were presented on the screen. Each image was calculated using the position of the appropriate eye with respect to the screen, 21±3 ms earlier (mean delay ± standard deviation (SD): see Brenner et al. 1998). With the aid of the specially designed set-up (Brenner et al. 1998), we were able to determine the moment when the target appeared with the 4-ms resolution with which the position of the rod was determined.

Procedure

Subjects were told that they had to hit each stationary or moving spider with the tip of the rod. The hand was allowed to hit the screen. They were to hit the target as soon as possible, minimising not only their movement duration, but also their reaction time. Subjects were free to position themselves and the chair. They all spontaneously chose a starting position with the hand beside the shoulder, and thus viewed the screen slightly from the side. From this position, 1.0 cm on the screen corresponded to approximately 1.0 degree of viewing angle.

Before each trial the subject had to move the tip of the rod to within 5 cm of a pre-set position 40 cm away from the screen. This starting position was opposite the screen's vertical midline, at the same height as the screen's centre. If the rod was not within the starting range, a 3D virtual line sticking out of the screen indicated the starting position, and a written instruction appeared that told the subject in which direction to move his or her hand. The rod's exact starting position varied between trials. The position at which a target appeared on the screen was adjusted to the rod's starting position, so that the position with respect to the rod was precisely defined. The spider appeared when the rod had been stationary within the starting range for a random period of 1–3 s (mean velocity <0.005 m/s).

During the experiment, the spider was considered to have been hit when the centres of the rod's tip and of the spider came within

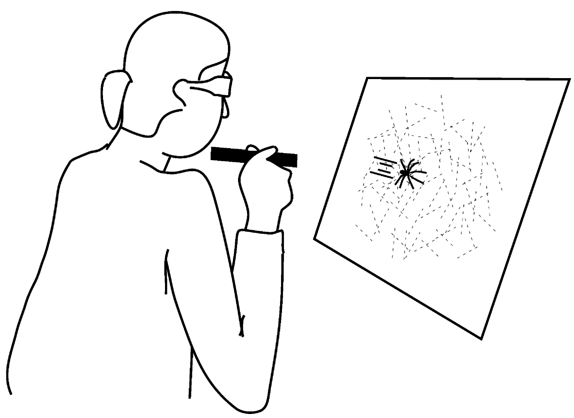

Fig. 1 Schematic view of the experimental set-up

18 mm of each other. If the spider was hit, it looked squashed. If the screen was hit outside this 18-mm range, the spider was missed. It then ran away from the rod. For example, if the subject hit below the spider, it would run upwards. The background was refreshed after each trial.

Each subject practised until he or she felt comfortable with the task (usually 10–20 trials). The room lights were off, so the subject did not see the computer monitor but only the stereo-image that it generated. An experiment of 80 trials lasted 10–15 min.

Data analysis

Of the overall total of 6,818 trials, 141 were discarded either because the infrared markers became invisible before the screen was reached, or because the rod was already moving when the target appeared. Trials on which the subject missed the target were included in the analysis.

As the position where the target appeared was adjusted to the rod's initial position, we do not expect systematic adjustments in the direction perpendicular to the target's motion. We therefore ignored this component of the hand's movement and analysed the projections of the movements on plane spanning the target's movement and the tangent to the hitting screen (Smeets and Brenner 1995). The reaction time (RT) was defined as the time between the target's appearance and the time when the rod's velocity towards the screen exceeded 0.1 m/s. The end of the movement was defined as the moment when the rod hit the screen. The movement time (MT) was defined as the time between start and end of the rod's movement. For the spatial analysis we took the rod's position at the RT as the origin of the movement.

We used the Savitzky-Golay method (Press et al. 1996) for smoothing the data. In accordance with this method, we performed least-square fits of a polynomial to both the left-right component and the forward component of the movements within a moving window. We used a second order polynomial and a window of 11 samples (5 before and 5 after the data point). The position and direction of the path in the centre of the moving window follow from respectively the linear and the quadratic term of the polynomials. The advantage of this method over conventional filtering is that it does not yield overshoots near a sharp change in velocity (such as the impact with the hitting screen).

Average paths of the rod were calculated for each movement condition and each subject (the individual paths were much like those presented in Smeets and Brenner 1995 and the control group in van Thiel et al. 2000). For calculating the average paths, the lateral movement component of each (smoothed) hitting movement was resampled at 151 points with equal intervals on the axis perpendicular to the screen. Each point was calculated as the linear interpolation between the two nearest time samples. Average paths were calculated from these resampled paths. To give an impression of the reliability of the *differences* between the average paths, the trajectories were printed with a thickness of the average intra-subject standard error divided by the square root of the number of subjects. Note that this measure does not represent the overall variability in the paths because it ignores all differences between subjects.

The direction in which the rod initially moved was determined at the tenth sample (out of the 151) of each subject's average paths. This was after moving about 2.5 cm towards the screen from the rod's initial position, corresponding with 68±12 ms (mean ± SD) after the RT. This choice was the result of a compromise. The direction of movement should be determined as early in the movement as possible, because the target's positions were approximately equated at the reaction time. Moreover, the hand should not yet have moved far because otherwise the direction of motion will also depend on the movement's past. However, the direction should not be determined too early because the signal to noise ratio increases with movement velocity. We determined the direction from each subject's average paths in order to increase the signal to noise ratio at the beginning of the movement.

Qualitative estimate of the influence of the target's velocity

As we outlined in the Introduction, we designed the experiments to include three sets of conditions that could be compared. Firstly, targets of the same velocity that appeared at different positions. Secondly, there were targets of different velocities that reached the same position around the time that the hand started to move. Thirdly, there were targets of different velocities that reached the same position around the time that the hand reached the hitting screen. If velocity information is used appropriately from the start, the hand's movement will start as if the subject aims at the position at which the target will be hit. Therefore, the rod's path should be the same when the target is hit at the same position, irrespective of difference in the target's velocity and in its position at the RT. On the other hand, if differences in target velocity do not influence the initial movement direction at all, the paths towards targets of different velocities will start in the same direction if the targets are at the same position around the time when the hand starts to move.

Quantitative estimate: the initial adjustment

For each subject and target velocity, we calculated a quantitative measure for the influence of target velocity on the initial direction of the rod's movement: the *initial adjustment*. To do so, we made use of the linear relationship that exists between the rod's initial movement direction and the target's current position (see Figs. 4B, 2C). [1] In three cases where this relation was not significant, the subject's data had to be excluded from the quantitative analysis. This was the case for one subject in experiments 1, 2 and 6. It was a different subject each time, and two of them were included as subjects in one or two other experiments. We derive the initial adjustment in "Appendix 1". In brief, it consists of the following steps: (1) determine the direction in which the hand initially moved for targets of the same velocity that appeared at different positions (Fig. 2B). (2) Use these values to calculate the relation (slope) between the hand's initial movement direction and the target's position (Fig. 2C). (3) Determine the hand's initial movement direction for targets of different velocities. (4) Use the slope from step 2 to convert the difference in movement direction (step 3) into a difference in target position. (5) Compare this difference in target position with the difference that one would expect, considering the difference in velocity and the remaining MT.

For clarity of the figures, the initial adjustment was calculated with respect to a reference velocity. In experiments 4 and 6, 12 cm/s was used as a reference, and in the others the average velocity.

Statistics

We examined whether the initial adjustment was influenced by the target velocity using a repeated measures ANOVA (α=.05). For post hoc testing we used Fisher's (protected) lsd procedure. Note that the choice of reference does not affect the statistics for the initial adjustment. However, the dependence of the MT on target velocity could influence the statistical tests. We therefore also repeated the tests in a manner that is less consistent with the figures. For this, we recalculated the initial adjustments without using a reference and using the subject's remaining MT *for each velocity* (rather than the subject's average remaining MT, see Eq. 6 in "Appendix 1"). Using this control, the same comparisons revealed significant effects in all

[1] For predicting the initial direction of movement from the target's position, Brenner and Smeets (1996) used the position 110 ms before the start of rod movement (a change in target position influences the path of the rod after a delay of 110 ms). However, later we (Smeets et al. 1998) proposed that subjects compensate for this visuomotor delay as long as nothing unexpected (like a jump of the target) occurs, so we here use the position of the target at the moment that the initial movement direction is defined.

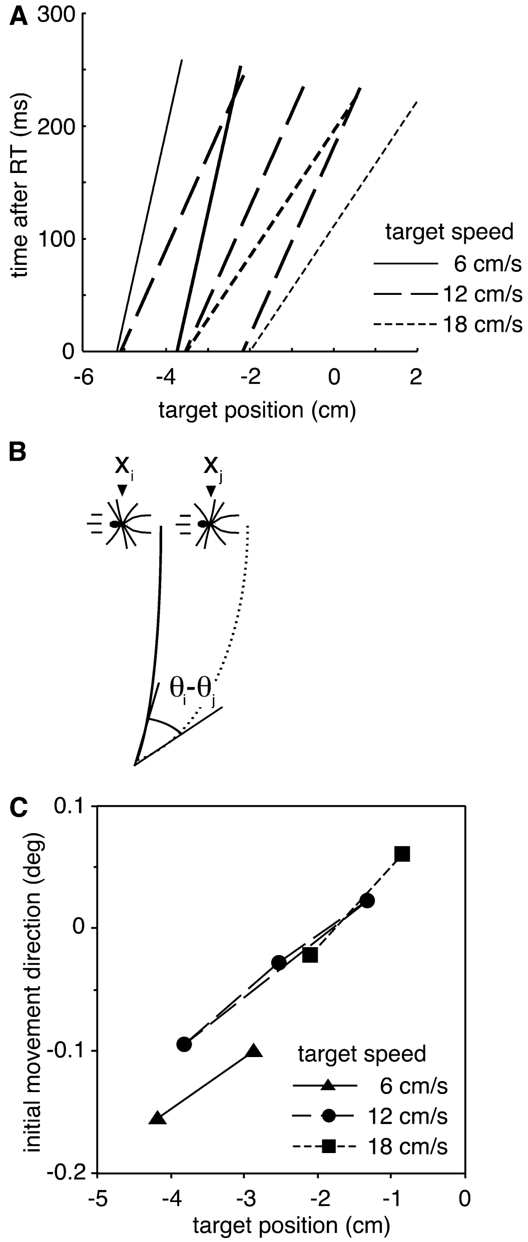

Fig. 2 **A** Average target positions in experiment 1. Time = 0 is when the hand started to move. Position = 0 is the hand's lateral position when the target appeared. The *ends of the lines* show the average time when the screen was hit. *Thick lines* are the target motions that belong to the movement paths shown in Fig. 3A. **B** Schematic view of two average paths with the initial movement direction, θ, and the lateral position of the targets, x. The *dotted path* will intercept target j and the *solid path* target i. **C** Target position x and initial movement direction θ for all seven targets of experiment 1 (averaged over subjects)

experiments. The outcomes of these analyses are therefore not presented.

Experiment 1: the basic effect

We analysed the rod's initial movement direction towards targets that appeared at different positions and moved with different velocities. The data of experiment 1 were also used in a different analysis (de Lussanet et al. 2001), in which we showed that the rod's initial movement direction and the final hitting position with respect to the target were influenced significantly by the velocity of the *preceding* target. In the present study we concentrated on the influence of the current target's velocity on the beginning of the movement.

Materials and methods

Each subject did 80 trials. Targets appeared in random order at a position that was defined with respect to the hand's current position (Table 1). The methods were as described in the "General methods" section. Fourteen subjects participated; one of them was excluded from the *quantitative* analysis because he did not reveal a consistent relation between initial movement direction and target position (so we could not calculate a meaningful initial adjustment).

Results

Figure 3A shows average paths towards the 5 targets that are shown with thick lines in Fig. 2A. On average subjects hit slightly in front of what we defined as the centre of the targets. 12.5% (between 0–27.5% for individual subjects) of the targets was missed in the left-right direction (but remember that misses were included in the analysis). The percentage of misses in the left-right direction was not significantly related to target velocity (linear regression on the subjects' percentages per kind of target; P=.45). Arrowheads in Fig. 3A mark the targets' positions at the RT and time of hit. On average, each of the targets was close to one of three positions at the RT. This shows that the chosen starting positions were adequate. The RT depended slightly on target velocity (P=.02, Table 2). The mean RT was slightly longer than the 250 ms to which we had suited the targets' positions (Table 2). In the extra time the 6 cm/s and the 18 cm/s targets respectively moved another 0.20 and 0.43 cm on average, as can be seen in Fig. 2A. The MT also depended on target velocity (Table 2). As a result of our choice of starting positions, the relation between the initial direction of the movement and the target's current position was not related to the target's velocity (Fig. 2B).

The *qualitative analysis* (Fig. 3A) reveals mixed results. On the one hand, the path towards the 6 cm/s target (white

Table 1 Lateral positions (in cm) of the targets in experiment 1 at various times after appearance. 0 cm is the hand's lateral position when the target appeared. Targets with the same position are printed in the same format

Velocity (cm/s)	6	6	12	12	12	18	18
N	10	10	15	10	15	10	10
0 ms	*−7.0*	−5.5	−8.5	*−7.0*	−5.5	−8.5	*−7.0*
250 ms	−5.5	*−4.0*	−5.5	*−4.0*	−2.5	*−4.0*	−2.5
500 ms	−4.0	−2.5	−2.5	*−1.0*	0.5	0.5	2.0

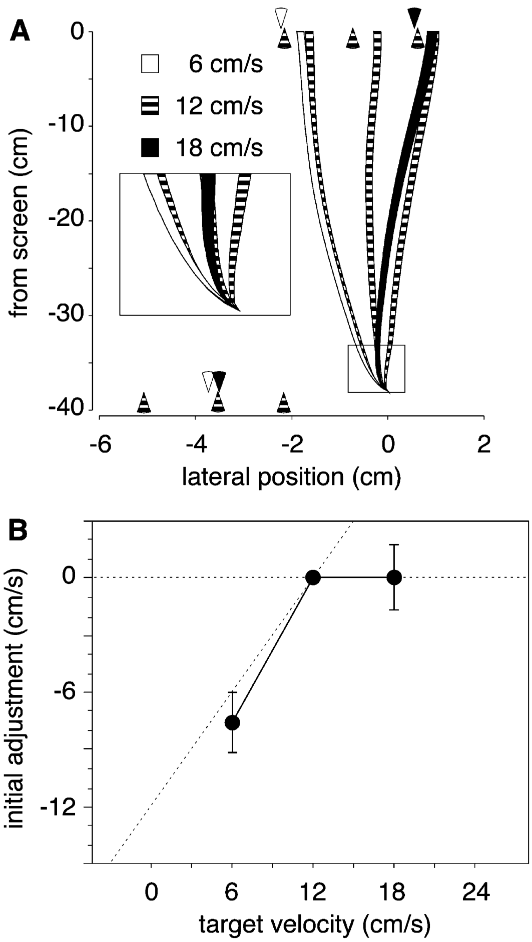

Fig. 3 **A** Average paths of the rod in experiment 1 for the targets indicated by *thick lines* in Fig. 2A. The thickness of the paths represents the reliability of the observed differences between the paths (see "Data analysis"). *Arrowheads* show each target's average position at the RT (*bottom left*) and the MT (*top right*). Note the different scales on the axes. The *inset* shows a 3 times magnification of the first 5 cm. **B** The initial adjustment with respect to 12 cm/s targets (with SEs). The *dashed diagonal line* shows the appropriate change in initial movement direction for the difference in target motion

curve) coincided with that to the 12 cm/s target with a similar *final* position (left striped curve). This indicates that the subjects *did* account for the difference in target velocity. On the other hand, the path towards the 18 cm/s target (black curve) started in the same direction as that towards the 12 cm/s target with a similar position at the RT (central striped curve). This indicates that the subjects did *not* account for the difference in velocity.

The *quantitative analysis* (Fig. 3B), that includes all seven conditions, confirms this. There was a significant main effect of target velocity (F=5.0, P=.016) which was clearly due to the initial adjustment at 6 cm/s (–7.6 cm/s) being different from the values at 12 and 18 cm/s (0.0 cm/s). The initial adjustment did not differ significantly between 12 and 18 cm/s in the post hoc test. Across subjects, the range for the initial adjustment was −21.8 to +1.5 cm/s at 6 cm/s and −18.4 to +17.0 cm/s at 18 cm/s.

Discussion

The qualitative and the quantitative method both revealed an influence of target velocity on the direction in which the hand starts to move. This implies that people can use the target's velocity to anticipate where they will hit the target when making a fast hitting movement. However, the influence of the target's velocity was only present with slow targets. Apparently, whether people use velocity information depends on the target's velocity.

Van Donkelaar et al. (1992) used an interception task that was similar to ours. In one of their experiments, the subjects' RT was decreased using an auditive go-signal. The initial direction of the hand's paths in that experiment was not correlated to the targets' velocity or position. In our experiment, the RT was slightly shorter for fast targets than for slow ones. Could this explain why the velocity of fast targets did not influence the hand's initial movement direction, while that of slow targets did? This seems unlikely. In experiment 1, the RT to 12 and 18 cm/s targets was just 5–10 ms shorter than that towards 6 cm/s targets. This difference was much smaller than the decrease in RT (>100 ms) imposed by the go-signal in van Donkelaar et al. (1992).

Table 2 The reaction time (*RT*) and movement time (*MT*) in each experiment. Shown are the means with standard deviations (SD) and the dependency on the target velocity (*Trend*). *Intra-SD* is the mean SD within subjects; *inter-SD* is the between-subjects SD. *Trend* represents the change in RT or MT that corresponds with a 6 cm/s increase in target velocity (with *P* values for the hypothesis that the trend = 0, from a covariance analysis). All subjects were included. The trends were calculated using all conditions with moving targets

	Experiment	Mean (ms)	Intra-SD	Inter-SD	Trend (ms per 6 cm/s)	*P*
RT	1	281	35	26	−4.9	.005
	2	286	40	27	−7.9	.004
	3	267	37	37	−2.8	.1
	4	284	44	29	−3.6	.3
	5	268	34	26	−4.1	.006
	6	283	44	39	−4.4	.04
MT	1	239	24	77	−16.1	<.001
	2	216	21	45	−11.1	<.001
	3	232	28	72	−15.7	<.001
	4	228	23	44	−8.5	<.001
	5	229	23	50	−12.0	<.001
	6	223	23	60	−10.4	<.001

Another possible explanation for these results is that subjects rightly judged (and used) the velocity of the 6 cm/s targets, but were unable to judge the velocity of the faster ones. If the target was a fast one, the subjects used the velocity of the preceding target instead (de Lussanet et al. 2001). This would explain why the initial adjustment was the same for 12 and 18 cm/s targets. The initial adjustment for fast targets would on average be appropriate for targets of 12 cm/s because on average the preceding target's velocity was 12 cm/s. For the 6 cm/s targets one would expect an initial adjustment of –6 cm/s (the difference between 6 and 12 cm/s).

Fast targets are more difficult to intercept than slow ones (Fayt et al. 1997), but this did not lead to more misses of the fastest targets. Thus, our subjects did follow an efficient strategy to deal with fast targets, despite apparently not always using velocity information from the start. In the subsequent experiments we try to find out what caused the difference between conditions with slow and fast targets. We first examine whether velocity is really the critical parameter, and not the position on the screen (experiment 2). Next (experiment 3), we examine whether the limited number of velocities, and in particular the large difference in relative velocity between 6 and 12 cm/s, could have made the 6 cm/s targets be considered separately (as the static targets were in Smeets and Brenner 1995). In experiments 4 and 5, we examined whether the velocity at which subjects stop to adjust depends on the range of target velocities used in the experiment. Finally, in experiment 6, we examined whether the limit for the influence of target velocity was absolute, or relative with respect to the targets' average velocity.

Experiment 2: target position does not explain the effect

In experiment 1 most of the fast targets were presented further to the right than most of the slow ones. This was so for the entire duration of the hand's movement (Fig. 2). One could therefore argue that it was not the magnitude of the target's velocity that was responsible for the effect on the initial movement direction. For example, a non-linear relation between initial movement direction and target position could explain the result as well. In experiment 2 we examine this possibility by presenting targets at more positions.

Materials and methods

Four targets of 6 cm/s and four of 12 cm/s were each presented on ten trials (80 trials in all). The targets of the same velocity appeared at different positions, 1.5 cm apart, in such a way that after 250 ms each 6 cm/s target had the same position as one of the 12 cm/s targets. Twelve subjects took part in this experiment. Further methods and analysis were the same as in experiment 1.

Results and conclusion

The RT and MT are given in Table 2. Figure 4A shows that target velocity did influence the initial movement direction towards 6 cm/s targets relative to 12 cm/s targets, though not as strongly as in experiment 1. The initial adjustment for the 6 cm/s targets was –3.9 cm/s (F=6.2, P=.030) rather than –6 cm/s. We will return to this value in section 7.3.

Figure 4B shows that there is a linear relationship between target position and the hand's initial movement direction. This was so for both velocities. Moreover, the slopes were very similar, showing that the influence of the targets' velocity on the direction of the rod's movement was constant for the whole range of target positions. We can conclude that the fact that target velocity was accounted for in some velocities, but not in all, cannot be due to the difference in the targets' average positions.

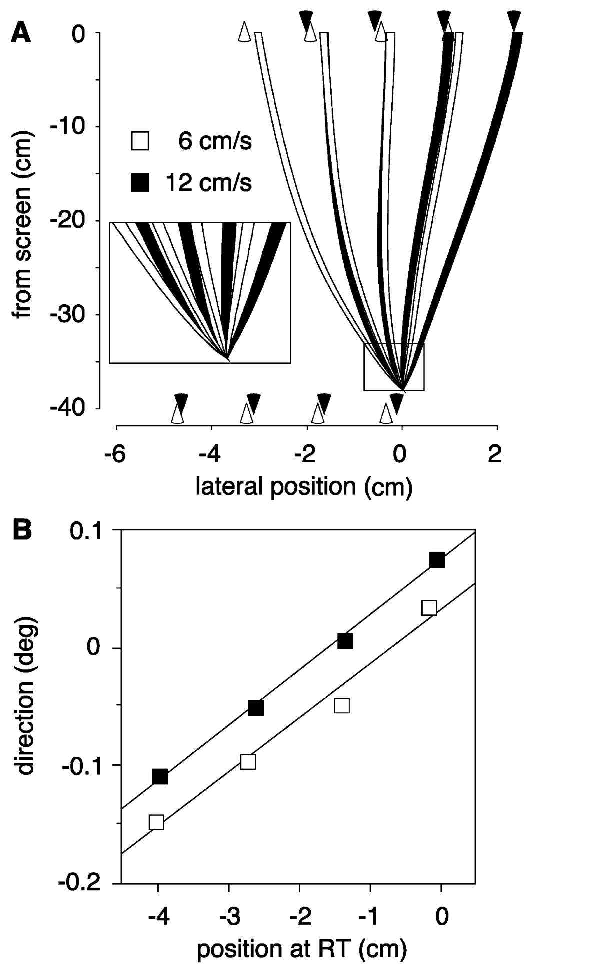

Fig. 4 **A** Average paths of the rod in experiment 2 for four targets of 6 cm/s (*white*) and four of 12 cm/s (*black*). See Fig. 3A for further explanation. **B** The relation between the target's average position at the RT and the average initial movement direction. *Open squares:* 6 cm/s; *slope*=0.046°/cm; R^2=0.98; *filled squares:* 12 cm/s; *slope*=0.047°/cm; R^2=0.99

Experiment 3: relative velocity differences did not make the slowest targets a separate class

In experiment 1, the targets' velocities differed by 6 cm/s, so the *relative velocity difference* between the two fastest targets was 50%, whereas that between the two slowest targets was 100%. One could hypothesise that this made the lowest velocity clearly different from the rest, encouraging the subjects to adopt a dichotomic strategy for "slow" and for "other" targets. Such a strategy would not be the same as using the slowest targets' correctly perceived velocity, because subjects could optimise performance separately for this class, rather than actually using the perceived velocity.

In the following experiment, targets of intermediate velocities were added, so that the relative velocity difference between the slowest targets and the next slowest targets was smaller. Moreover, the intermediate velocities made the slowest targets less conspicuous.

Materials and methods

In this experiment the seven conditions of experiment 1 (Fig. 2A), were combined with two conditions with targets of 9 and 15 cm/s. The 9 and 15 cm/s targets each appeared at positions that made them reach the same position as the central 12 cm/s target after 250 ms. Each subject did 110 trials. In 30 of them, targets moved at 12 cm/s. Targets with velocities of 6, 9, 15 and 18 cm/s were each presented in 20 trials. Twelve subjects took part in this experiment.

Results

Figure 5A shows that the average paths towards the 6, 12 and 18 cm/s targets were very similar to those in experiment 1 (Fig. 3A). The initial adjustments were also very similar to those in experiment 1 (Fig. 5B). It was –6.8 cm/s for the 6 cm/s targets, −3.0 cm/s for 9 cm/s targets, –1.0 cm/s for 15 cm/s targets and 0.3 cm/s for the 18 cm/s targets. However, the main effect of target velocity on the initial adjustment was not significant (F=1.6, P=.18). The RT and MT are given in Table 2.

Discussion

The influence of target velocity on the initial adjustment was not significant. Nevertheless, we consider the data to replicate the findings of experiment 1. We did not find any obvious reason why that data were more variable than in the other experiments. Furthermore, for 9 cm/s targets the initial adjustment was on average precisely the value expected for optimal use of velocity information, which is inconsistent with the hypothesis. We conclude that the difference between low and high velocities in experiments 1 and 3 was not caused by the slowest targets forming a separate class in a dichotomic strategy.

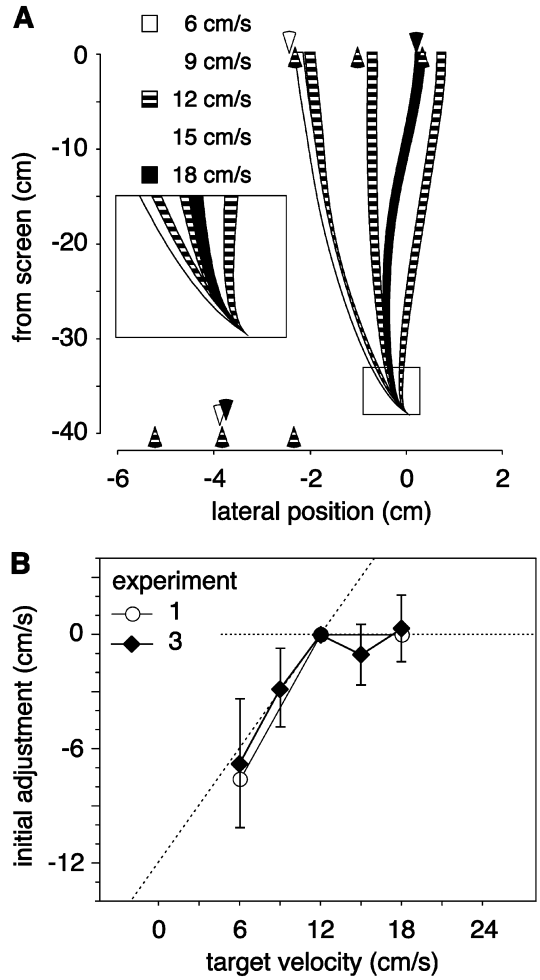

Fig. 5 **A** Average paths of the rod in experiment 3. Note that the paths to one of the 6 and one of the 18 cm/s targets and to the 9 and 15 cm/s targets are not shown. **B** The initial adjustment with respect to 12 cm/s targets (*filled diamonds*). See Fig. 3 for further explanation

Experiments 4 and 5: low and high velocities

In experiments 4 and 5, we will examine whether there is an absolute limit (i.e. 12 cm/s) to the velocity that people can use to guide the initial movement direction. To test this, we repeated experiment 1 twice: once with all targets 6 cm/s slower than in experiment 1 (experiment 4) and once with all targets 6 cm/s faster (experiment 5). If there is an absolute limit, the initial adjustment should be complete in experiment 4 (because the fastest targets move at 12 cm/s), and should be absent altogether in experiment 5 (because the slowest targets move at 12 cm/s).

Methods and results of experiment 4

The targets were as in experiment 1, but with velocities of 0, 6 and 12 cm/s. All targets appeared 3.5 cm further to the right than in experiment 1, so that they were hit at similar positions. In addition, the targets' relative positions at the RT were very similar to those in experiment 1 (compare arrowheads in Figs. 3A and 6A). RT and MT are given in Table 2. Fourteen subjects took part in the experiment.

The average path towards the stationary target (Fig. 6A) almost coincided with the path towards the 6 cm/s target that had a similar position when hit. The path towards the 12 cm/s target, however, started in the same direction as that towards the central 6 cm/s target (which was at a similar position at the RT). The initial adjustment (Fig. 7) confirms this result. It was –7.6 cm/s for the 0 cm/s targets and negligible for the 12 cm/s targets. There was a significant main effect of target velocity in the ANOVA on the initial adjustment (F=17.8, P<.0001). The initial adjustment at 0 cm/s target velocity differed significantly from that at 6 cm/s and that at 12 cm/s target velocity.

Methods and results of experiment 5

The targets were as in experiment 1, but all targets appeared 2 cm further to the left and moved 6 cm/s faster:

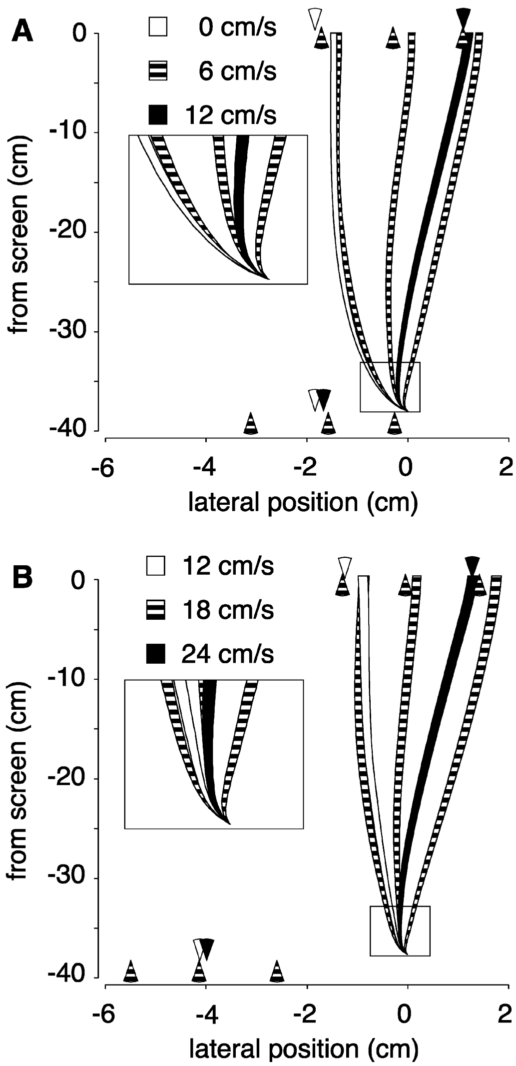

Fig. 6 Average paths of the rod in experiment 4 **(A)** and experiment 5 **(B)**. Note that only the paths to certain targets are shown. See Fig. 3A for further explanation

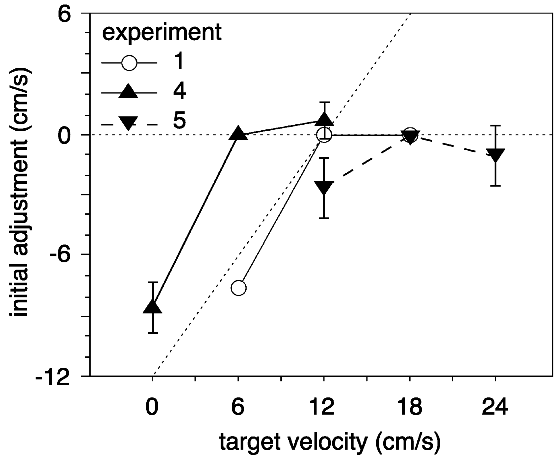

Fig. 7 The initial adjustment for experiments 1, 4 and 5 (the reference velocity was 12, 6 and 18 cm/s respectively). See Fig. 3B for further explanation

at 12, 18 or 24 cm/s. The same fourteen subjects of experiment 4 took part in experiment 5. One of them was excluded because he did not reveal a consistent relation between target position and initial movement direction. One subject did only 58 trials because the experiment stopped prematurely due to a software error.

The average path towards one of the 24 cm/s targets (black curve in Fig. 6B) started in the same direction as that towards the middle 18 cm/s target (middle striped curve). For these two targets, the positions coincided at the RT (see arrowheads at the bottom). This means that the rod's initial movement direction did not depend on the target's velocity. RT and MT are given in Table 2.

The left and the central 18 cm/s targets (arrowheads in Fig. 6B) had the same position as the 12 cm/s target at the RT and the time of the hit respectively. The path towards the 12 cm/s target started in a direction in between these targets. Figure 7 shows that the initial adjustment for 12 and 24 cm/s was small (respectively –2.7 and –1.0 cm/s). There was no significant effect of target velocity on the initial adjustment (F=0.5, P=.6). The initial adjustments at 18 cm/s and 24 cm/s were significantly below the values expected for complete compensation (18 cm/s: t=−2.1, P=.28; 24 cm/s: t=−3.1, P=.005).

Discussion

The result of experiment 1 and 3 can be explained with a transition at 12 cm/s above which the target's speed does not influence the hand's movement direction. The almost complete lack of initial adjustment in experiment 5 is consistent with such an absolute limit. However, the lack of initial adjustment for the comparison between 6 and 12 cm/s targets in experiment 4 cannot be explained by a transition at 12 cm/s. Instead, if the average velocity is below 12 cm/s the transition could be at the average velocity. We will call this a *relative transition*. Experiments 1, 3 and 4 would be in agreement with such a relative transitional velocity. In the final experiment 6 we will test whether such a relative transitional velocity is a likely explanation.

Experiment 6: combining experiments 1 and 4

Accounting for the targets' velocities when below average but not when above average could explain the findings about the hand's initial movement direction in experiments 1–4. If a transition occurs at the average velocity, then we can make a prediction for the following experiment, which combines the velocities of experiments 1 and 4 (0, 6, 12 and 18 cm/s). We predict that the initial adjustment between 0 and 6 cm/s will be as in experiment 4, and that there will be no initial adjustment between 12 and 18 cm/s. The initial adjustment between 6 and 12 cm/s will depend on the average velocity of all targets. Thus, if the average velocity is 8.4 cm/s, the prediction is that only the difference between 6 and 8.4 cm/s will be accounted for.

Materials and methods

In experiment 6 we used the seven conditions of experiment 1 (Fig. 2A), but in addition there were three conditions with stationary targets. Each stationary target appeared at one of the three positions that the 12 cm/s targets reached after 250 ms. There were ten conditions, that each consisted of ten trials: three conditions with 0 cm/s and with 12 cm/s targets, and two with 6 cm/s and with 18 cm/s targets (the average velocity was therefore 8.4 rather than 9.0 cm/s). Twelve subjects took part in this experiment. One of them was excluded because he did not reveal a consistent relation between target position and initial movement direction.

Results

The RT and the MT are given in Table 2. The path towards the 18 cm/s target shown in Fig. 8A started in a direction that corresponds with that towards the 12 cm/s target that was at about the same position at the RT. The path towards the 6 cm/s target (Fig. 8A) started in a direction that corresponded with that towards the 12 cm/s targets that were at about the same position when hit. Figure 8B shows that for the comparisons with slower targets all paths towards targets that were hit at the same position also started in the same direction.

The initial adjustment between 0 and 12 cm/s and between 6 and 12 cm/s were respectively –13.2 cm/s and –4.6 cm/s (Fig. 8C). The initial adjustment at 18 cm/s was negligible (1.0 cm/s). There was a significant main effect of target velocity on the initial adjustment (F=15.2, P<.0001). The post hoc tests showed that the initial adjustment at 0 cm/s target velocity differed significantly from the initial adjustments at the other (higher) velocities. In addition, the difference between the values at 6 and 18 cm/s was significant.

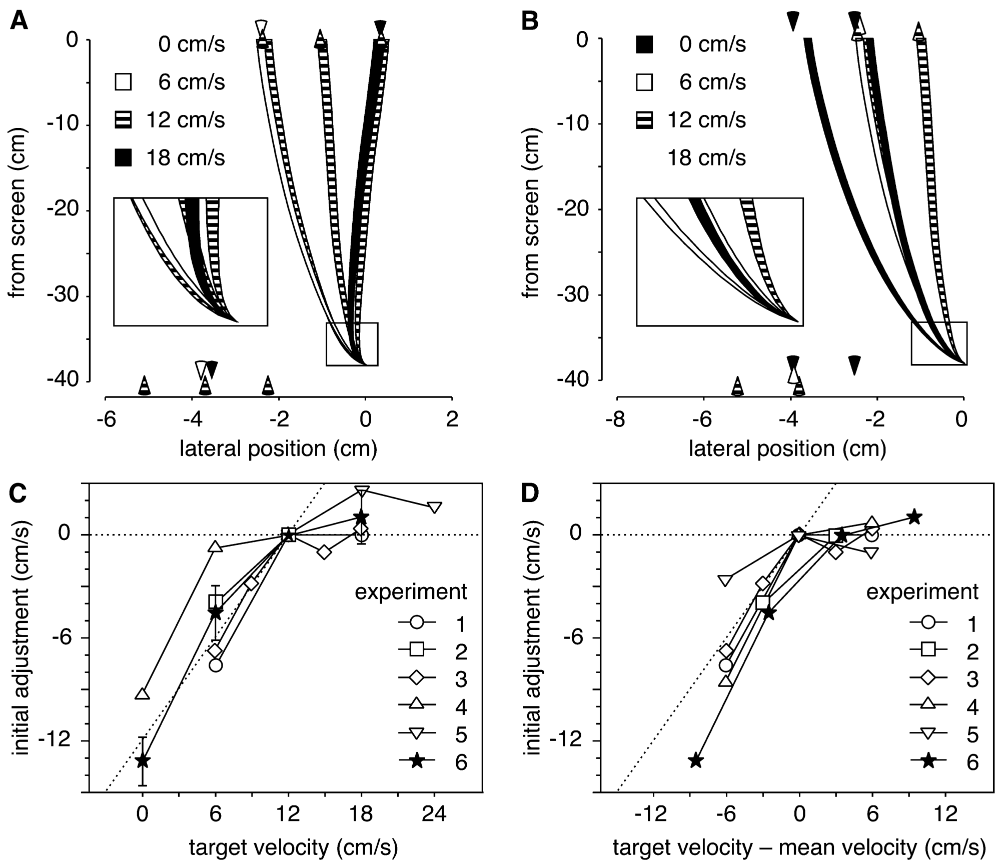

Fig. 8 A, B Average paths of the rod in experiment 6. **A** Selection of paths corresponding with the paths shown in Fig. 3A (experiment 1). **B** Selection of paths showing the paths toward slower (and static) targets. **C** The initial adjustment as a function of the difference between the target's velocity and the average velocity (the average velocity for experiments 1–6 was respectively 12, 9, 12, 6, 18 and 8.4 cm/s). **D** The same as in **C**, but displayed slightly differently. The initial adjustment was calculated with respect to the average velocity in experiments 1, 3, 4 and 5, and with respect to 12 cm/s in experiments 2 and 6 (because there were no targets moving at the average velocity)

Discussion

As predicted, the initial adjustment between 0 and 6 cm/s was almost the same as in experiment 4 (respectively 8.6 and 7.6 cm/s) and was almost zero between 12 and 18 cm/s (1.1 cm/s). The average initial adjustments of 13.2 cm/s (between 0 and 12 cm/s target velocity) and 4.6 cm/s (between 6 and 12 cm/s) were larger than the predicted values of 8.4 and 2.4 cm/s. This is consistent with the other experiments: when plotted as a function of the average velocities, the data of the experiments 1, 4 and 6 show this pattern (Fig. 8D). The velocity of targets moving faster than average was not accounted for (the initial adjustment is about zero for positive values of relative velocity). For targets moving slower than average, the velocity was accounted for in the initial adjustment, and mostly over-accounted for.

General discussion

In the present study, we examined unrestrained hitting of targets that moved to the right across a screen. The results show that target velocity influences the hand's movement direction from the start. For low target velocities this influence is even stronger than one would expect from velocity being used to predict where the target will be intercepted. In contrast, at high velocities the influence of target velocity on the initial direction of the hand's movement was completely absent.

We quantified the influence of target velocity with a measure that we called the *initial adjustment* (see "Appendix 1"). The initial adjustment between the two slowest targets over-compensated for the difference in target velocity by the same factor (1.3–1.4) in experiments 1, 3, 4 and 6. Comparing the conditions in these experiments reveals that velocity compensation does not depend on the precise velocity of the slowest target (0 or 6 cm/s) or on the difference between low and high velocities (12 or 18 cm/s).

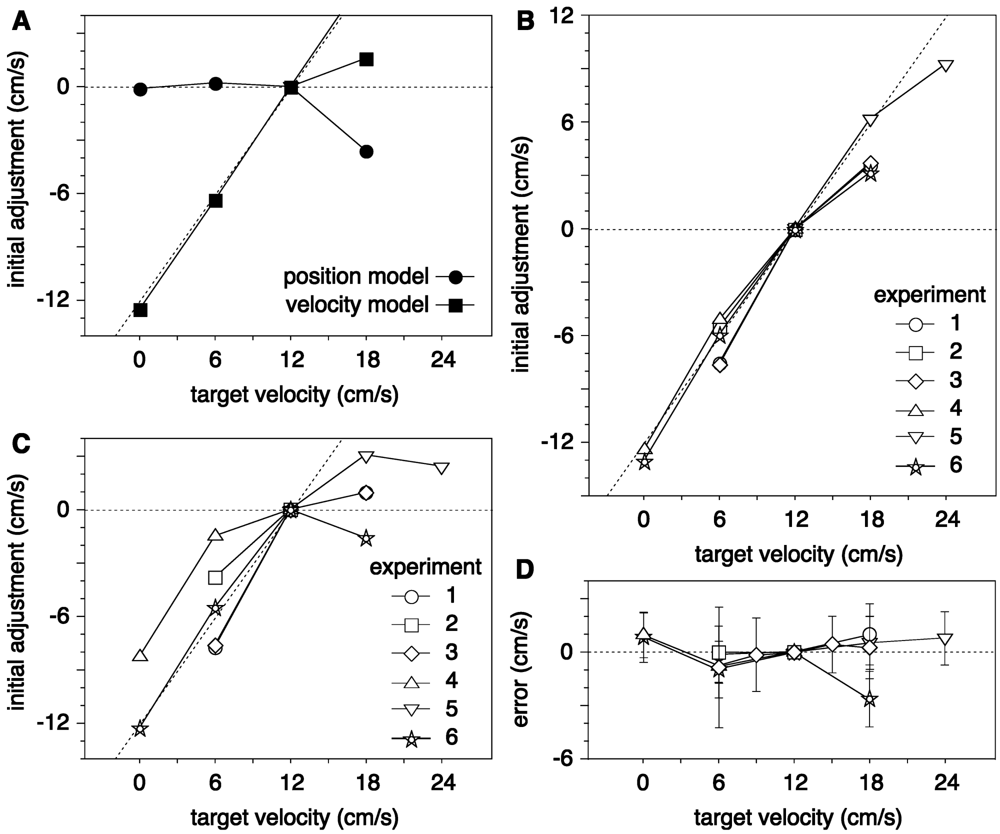

Fig. 9A–D Model predictions. **A** Initial adjustment predicted with two models for data from Smeets and Brenner (1995: experiment 3, stationary background). In the *position model,* target velocity has an indirect influence in that the subject's expectation of where he will hit the target changes ("Appendix 2"). The initial adjustment reduces at high speeds because subjects move faster towards fast targets. In the velocity model the target speed influences the initial adjustment directly, but not by influencing the subject's expectation of where he will hit the target, so the initial adjustment is not perfect. **B** The initial adjustments for the current 6 experiments predicted with the *velocity model*. It is assumed that target velocity always influences the hand's movement direction from the start. **C** Predictions with the same (velocity) model and the same model parameters as in **B**, but assuming that a "fast" target's velocity only starts to influence the direction 62 ms after the hand started to move. "Fast" means above 12 cm/s and including 12 cm/s in experiments 3, 4 and 6. For details see text and "Appendix 2". **D** The difference between the model predictions **(C)** and the real data (Fig. 8C)

At the other end of the range, velocities above the mean velocity (right part of Fig. 8C) never influenced the hand's initial movement direction, so we assume that there is a relative velocity limit. However, the initial adjustment for the lowest velocity in experiment 5 (12 cm/s) is also very modest. This cannot be explained by a relative velocity limit (Fig. 8D). The results of experiment 5 suggest that there is a second, absolute limit of about 12 cm/s, above which the initial movement direction is not matched with the target's velocity.

Many studies show an influence of target velocity on the hand's velocity and acceleration. The pattern of these influences is different from ours. For example, the influence of target velocity on the hand's acceleration towards the target (and on the movement time) is not known to depend on the targets' range of speeds (Bairstow 1987; Brenner et al. 1998; Brouwer et al. 2000; Dubrowski et al. 2000; Fayt et al 1997; van Donkelaar et al. 1992).

The quantitative measure, the initial adjustment, was based on the assumption that the target's velocity is used to predict where the target will be hit. An alternative explanation is that velocity information influences the movement in a different way, independent of the role of the target's position. We explore this alternative explanation using a model for the control of the hand's movements.

Model predictions for the initial adjustment argue for a quantitative influence of target velocity

An illusory change of target velocity, caused by a moving background, influences the hand's velocity. Intriguingly though, the direction in which the hand moves is not affected by this illusion (Smeets and Brenner 1995; Brouwer et al. 2002). The simplest explanation for this difference is that velocity information is not used to direct the hand to the target (Smeets and Brenner 1995). Following this explanation, Smeets and Brenner argued that a moving target's continuously *changing position* influences a subject's prediction for where he will hit it, and thus influences the shape of the hand's path. Smeets and Brenner (1995) modelled the influence of differences in position and velocity of rightward moving (or stationary) targets, on the hand's lateral movements. The model (further called *position model*, see "Appendix 2") was a linear, damped oscillator with just two parameters, stiffness and damping. In accordance with the simplest explanation, the model assumed that the position of interception was continuously predicted from the target's current position, using an estimated (not the actual) target velocity. Note that the position model does contain target velocity, but its influence is indirect, through the changing position, and thus the changing prediction of the target's final position.

Later, however, de Lussanet et al. (2002b) improved the model by using speed-dependent damping ("Appendix 2", Eq. 9). It still did not use the velocity to predict the target's future position, and it had the same number of parameters. This model, hereafter called *velocity model*, predicted the experimental data of Smeets and Brenner (1995) much better. We explain in "Appendix 2" how we used the model to predict the initial adjustment. Figure 9A shows that the position model and the velocity model predict very different curves for the relation between target velocity and the initial adjustment. This result shows that the initial adjustment can depend on target velocity without using it to predict the position of interception. Moreover, it shows that the initial adjustment is not necessarily proportional with target velocity. This is not due to a complicated behaviour of the model, but solely due to the shorter movement times towards faster targets.

We used the velocity model to predict the initial adjustments for our current data (Fig. 9B), in agreement with our findings that high velocity does not influence the initial movement direction. The velocity model fails for high velocities (compare Figs. 8D and 9B). The velocity model's good predictions for the low velocities provide additional support for the quantitative use of velocity information to direct the hand.

Low speed takes long to detect, but high speed probably takes long to quantify

For several reasons, our finding that the initial movement direction is suited to target velocity when intercepting slow targets, but not when intercepting fast ones, needs an explanation. Firstly, ignoring the target's motion has larger consequences for fast targets than for slow ones, and is therefore not a clever strategy. Secondly, it is unlikely that lateral (left-right) hand acceleration is a limiting factor in adjusting to the target's speed, because the initial forward acceleration was always much larger than that in the left-right direction (2–10 times). Thirdly, high velocities take less time to detect than low velocities (Tynan and Sekuler 1982; van Doorn and Koenderink 1982). One could therefore argue that if the time that the target is visible before the rod starts to move (the RT) is long enough to take the velocity of slow targets into account, this time should also be long enough for fast ones. However, for quantitative use of velocity it is not the time needed to *detect motion* that is critical, but the time needed to *judge the velocity.* The latter may well be *longer* for fast targets than for slow ones.

Indeed, there is reason to believe that judging high velocity takes longer than judging low velocity. Firstly, there is evidence suggesting that humans have independent mechanisms for detecting slow and fast retinal motion (Verstraten et al. 1998). The transition between the detection mechanisms for low and high velocity detection differed between subjects, but was around 10°/s. Only the mechanism for slow retinal motion appears to yield quantitative information. This finding is confirmed by observations in smooth pursuit eye movements. The correlation between the initial acceleration of smooth pursuit eye movements and target velocity levels off for targets that move faster than about 10°/s (Carl and Gellman 1987; Niemann et al. 1994; Kao and Morrow 1994). In our experimental set-up, 1 cm of target movement corresponded with about 1 degree of visual angle, so this is consistent with our suggested absolute velocity limit of about 12 cm/s. For fast targets, initiation of smooth pursuit eye movement is more strongly correlated with the velocity of the preceding target (Kao and Morrow 1994), as was the direction of the hitting hand (de Lussanet et al. 2001).

We tested the plausibility of the idea that high velocity takes longer to judge, by implementing it in the velocity model (Fig. 9C). We introduced a delay of 62 ms for the use of velocity information for high velocities, i.e. those above the absolute and/or relative velocity limits. Figure 9C, D shows that under this assumption the velocity model predicts the initial adjustment very well for all experiments. Thus, our data could be consistent with the *quantitative* use of velocity information as soon as it becomes available in the brain.

The global influence of long and short average reaction times also supports this view. The reaction times in the present study were about 100 ms shorter than those in Smeets and Brenner (1995) were. This is consistent with the fact that in Smeets and Brenner (1995) all velocities appear to have influenced the movement from the start, whereas in the present experiments not. In the present study, the subjects apparently did not have quantitative knowledge of fast target's velocity at the beginning of the movement.

In addition, in the present study, the time after the target's appearance when paths towards targets of the same speed but different positions went in different directions was not shorter for the subjects with the shortest reaction times (data not shown). Finally, when van Donkelaar et al. (1992) reduced the RT by giving an auditory start signal, this increased the time (measured from the reaction time) that paths towards targets of different position and velocity started to go in different directions.

Relation to previous studies

Brenner and Smeets (1996) found a different response for moving and stationary targets. For moving targets, however, they did not find a dependence of the initial direction on target velocity. This was presumably because they tested across all non-zero velocities at once (6, 9, 12, 15 and 18 cm/s; the mean velocity was 9 cm/s because there were many static targets). According to our present findings, there would possibly only have been an effect for a comparison between the two lowest velocities.

Van Thiel et al. (2000) used the same measure as Brenner and Smeets (1996) to interpret interceptive movements. They did find a significant effect of target velocity on the initial movement direction ("Initial Estimate", 0 cm/s not included). A possible explanation is that the hemiplegic subjects seemed to have a stronger influence of target velocity than the control group. The effect for the healthy subjects was of the same magnitude as that of Brenner and Smeets (1996) and may not have been significant on its own. It may sound surprising that the effect was stronger in the patients. The patients' RTs were on average 112 ms longer than those of the healthy subjects, which may be due to difficulties in starting up a movement (Brown et al. 1989). A side effect of this considerable delay in the start of the movement is that the subject has more time to gather information about the target's velocity before the hand starts to move. An experiment by van Donkelaar et al. (1992) supports this idea. They increased the subjects' reaction time by using an auditive go-signal. In this experiment, with increased reaction times, they did find a higher correlation between the initial direction of the hand's paths and the targets' velocity than in the experiment without a go-signal. Apparently, healthy subjects' control mechanisms for guiding the rod to the target are so good that they can start the movement before information about the target's velocity is fully considered (see above).

We have presented evidence for a quantitative use of velocity information in guiding the hand when intercepting a target. This influence is probably related to the control of smooth pursuit eye movements, and is not used to predict the position of interception.

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Appendix 1: the initial adjustment

Below we derive the initial adjustment. First, we describe how we estimated the slope of the relation between target position and initial movement direction for each subject (assuming that the subjects judge the difference in target position correctly). Subsequently we use this relation to calculate each subject's initial adjustment. The relation between target position and movement direction can only be calculated for targets with the same velocity. Targets of each velocity appeared at several different positions in all experiments described in the present study. The initial movement direction was calculated from each subject's average paths (see "General methods"). We used average paths instead of individual movements to obtain a better signal to noise ratio.

Let N be the number of pairs of targets (in a single experiment) with the same velocity but a different position of appearance. For example, in experiment 1 (Table 1, Fig. 2A) there were two conditions with 6 cm/s targets (conditions 1 and 2), three conditions with 12 cm/s targets (3, 4 and 5) and two with 18 cm/s targets (6 and 7). If we number these seven conditions, the N=5 combinations of conditions i, j with equal velocity would be $i, j \in \{1, 2; 3, 4; 3, 5; 4, 5; 6, 7\}$. Further, let θ_i be the initial direction of the rod's average path in condition i, and let x_i be the average target position at that same moment (Fig. 2B). For each subject we derived a single constant S for the relation between x and θ (Fig. 2C):

$$S = \frac{1}{N} \sum_{i,j} \frac{x_i - x_j}{\theta_i - \theta_j} \tag{1}$$

There was a significant (t-test across the N combinations, α=.05) positive relationship between target position and initial movement direction in 75 out of a total of 78 experimental sessions (6 experiments, 12–14 subjects in each). In the three cases where this relation was not significant, the subject's data had to be excluded from the quantitative analysis (though not from the qualitative analysis). The estimated slope Sallows us to express differences in initial movement direction as differences in "aiming position" (x^{aim}), even for targets of different velocities. Let k and l be conditions with targets of different velocity. Then

$$x_k^{aim} - x_l^{aim} = S \cdot (\theta_k - \theta_l). \tag{2}$$

The difference in aiming position is the combined effect of the differences in position at that moment (x_k–x_l), and ones that are expected to arise because differences in velocity are taken into account $\left(x_k^{adj} - x_l^{adj}\right)$. Thus:

$$x_k^{aim} - x_l^{aim} = x_k - x_l + \left(x_k^{adj} - x_l^{adj}\right). \tag{3}$$

In order to express $\left(x_k^{adj} - x_l^{adj}\right)$in terms of a difference in the velocity that is used to guide the hand (i.e. the initial adjustment, $v_{k,l}^{adj}$) we have to divide it by the remaining movement time (rMT). Since the MT differed considerably between subjects, each subject's average rMT was used for his or her data.

$$v_{k,l}^{adj} = \frac{x_k^{adj} - x_l^{adj}}{rMT}. \tag{4}$$

Filling in (2) and (3) solves Eq. 4:

$$v_{k,l}^{adj} = \frac{S \cdot (\theta_k - \theta_l) - (x_k - x_l)}{rMT}. \tag{5}$$

We always present the initial adjustment with respect to the average of the three or four conditions with the reference velocity L (four in experiment 2, three in the other experiments). Thus, the initial adjustment for condition k becomes:

$$v_{k,L}^{adj} = \frac{(S \cdot \theta_k - x_k) - \overline{(S \cdot \theta_L - x_L)}}{rMT}. \tag{6}$$

Targets of each velocity appeared at several (2–4) different positions. In order to obtain one value of the initial adjustment per target velocity per subject, these 2–4 values were averaged.

Note that for S, θ, $x$and rMT we used the measured values for each individual subject in the experiment that is analysed.

Appendix 2: models with and without use of target velocity

The modelling approach that we followed is described in de Lussanet et al. (2002b), where we predicted the hand's path with use of target velocity (*velocity model*) and without the use of target velocity (*position model*). Here we will first briefly describe the two models and then how we implement them to predict the initial adjustments for the data of experiment 3 in Smeets and Brenner (1995) and for the data of the six current experiments. In all cases, we applied the model to movement paths averaged over those of all subjects.

The hand's path was modelled as continuously accelerating towards the screen on which the target was presented and as a damped linear oscillator in the perpendicular component, the direction in which the target moved. The acceleration towards the screen was chosen such that for each condition the modelled movement time was the same as the real average movement time. In the *position model,* the oscillator describes the differences between the paths towards targets at different positions and of different velocities. With$x$ being the hand's position and $q$being the equilibrium point (in which the hand's acceleration is 0), the general differential equation for such an oscillator is:

$$v_{k,L}^{adj} = \ddot{x} + b \cdot \dot{x} + k \cdot (x - q) = 0 \tag{7}$$

(each dot over a variable represents the derivative with respect to time). Stiffness, k, and damping, b, were fitted for movements towards targets that only differed in the position on the screen where they appeared, with respect to the hand's starting position. We used the same values of b and k for the position model and the velocity model. For the data from experiment 3 in Smeets and Brenner (1995) we used paths towards stationary targets, averaged over all subjects (as in de Lussanet et al. 2002b). The fitted stiffness b=7.96 s^{-1} and the damping k=61.0 s^{-2}. In the present study, the movement times were much shorter than in Smeets and Brenner (1995) so we had to fit a new b and k. For this we used the movements towards the 12 cm/s targets in experiment 1, again averaged over all subjects. The fitted stiffness b=22.7 s^{-1} and the damping

k=146.0 s^{-2}. These values were used to predict the initial adjustments of all six experiments.

The equilibrium point is not necessarily stationary. We assumed that it is the continuously updated position where the subject expects to hit the target. The rate at which the equilibrium point changes its position depends on the subject's expectation of the target's velocity, v. We used the average velocity (de Lussanet et al. 2001). With t being the time from which the hand moves (the reaction time, RT), s_{RT} the target's position at the average RT and $\dot{s}$ the target's velocity, q can be calculated as:

$$q(t) = s_{RT} + \dot{s} \cdot t + v \cdot (MT - t) \quad (8)$$

(where t<MT, the movement time).

In the *position model,* target velocity thus only influences the hand through the changes in position. In the *velocity model,* the hand is damped relative to the equilibrium point, rather than to space. The damping coefficient thus acts on the difference between the target's velocity and the average velocity: $\dot{q} = \dot{s} - v$. The differential equation for the velocity model is thus:

$$\ddot{x} + b \cdot (\dot{x} - \dot{q}) + k \cdot (x - q) = 0 \; . \quad (9)$$

For the (imaginary) case that the MT would be independent of target velocity, the velocity model would predict that the initial adjustment scales proportionally with target velocity. As the MT really decreases with target velocity, we expect that the relation flattens off with increasing velocity. The solutions for differential Eqs. 7 and 9 are given in de Lussanet et al. (2002b) as well as further details on the modelling results.

To predict the initial adjustment we first predicted the hand's path, using the velocity model with the fitted values for b and k given above, the target's velocity, the target's average position at the RT (Table 2), and the average MT (Table 2). In some simulations, we incorporated a delay of 62 ms before velocity information was used. In these cases, the first 62 ms of the path was predicted using zero velocity (which is in effect the same as the position model), whereas the rest of the path was predicted using the actual target velocity. The initial adjustment was calculated from the predicted paths in the same way as it was calculated from the measured paths (see "Appendix 1").

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