Exp Brain Res (2000) 133:242–248
Digital Object Identifier (DOI) 10.1007/s002210000371

RESEARCH ARTICLE

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Hitting moving objects

The dependency of hand velocity on the speed of the target

Received: 9 July 1999 / Accepted: 31 January 2000 / Published online: 25 March 2000

Abstract In previous studies, subjects did not hit slowly moving objects as quickly as fast ones, despite being instructed to hit them all as quickly as possible. In those studies the targets moved at constant but unpredictable velocities, and it has been suggested that subjects were unable to adjust the hand's path to suit the velocity of the target. To compensate for this, they adjusted the speed of their hand to that of the target (speed coupling). According to this hypothesis, speed coupling is necessary only when subjects are unable to correctly predict the next target velocity and only if they have to be accurate. We show here that decreasing the uncertainty about the upcoming target's velocity or enlarging the tip of the hitting weapon does not make speed coupling disappear. Moreover, there is a negative correlation between hand velocity and strength of speed coupling, whereas the hypothesis predicts a positive correlation. The hypothesis is therefore rejected. We propose that speed coupling is a result of different speed-accuracy tradeoffs applying to different target velocities.

Key words Motor control · Velocity · Interception · Arm movement · Vision · Human

Introduction

When you play tennis or catch a ball, you perform a task that is not as simple as it may seem. The racket or hand has to reach an appropriate position within quite narrow time limits and with an adequate velocity and orientation. It is unknown how people accomplish this feat, considering the temporal limitations imposed by neuronal delays and the quickly approaching ball.

A wide variety of tasks have been used to study interception of moving objects. Subjects have had to catch (Savelsbergh et al. 1992) or hit (Bootsma and van Wieringen 1990; Fayt et al. 1997) balls, grasp objects rolling down a ramp (Carnahan and McFadyen 1996) or driven by a little motor (Wallace et al. 1992), or they had to intercept targets on a screen using a tool (Bairstow 1987; Smeets and Brenner 1995) or their hand (van Donkelaar et al. 1992). In spite of the differences between the tasks, a speed coupling was found in all of these studies: the hand velocity depended on the target velocity. More specifically, subjects did not move their hands as quickly to slowly moving objects as they did to fast objects, even if instructed to always move as quickly as possible (Smeets and Brenner 1995). Two possible explanations for this coupling of the speed of the hand to target speed have been given in the literature.

van Donkelaar et al. (1992) suggest that speed coupling can be explained by the fact that movements made to targets in ipsilateral visual space are generally faster (Fisk and Goodale 1985). This explanation could apply to their task, because their subjects had to intercept targets moving from the left to the right of a screen, using the right hand. By the time the hand reached the screen, fast targets had moved further to the right, into the subjects' ipsilateral space, whereas slow targets were still on the left, contralateral side. However, subjects did not intercept fast objects in ipsilateral and slow objects in contralateral space in all the studies mentioned above, so this can certainly not be the whole explanation. Furthermore, Smeets and Brenner (1995) presented static targets at three different positions and found that movement time did not depend systematically on position in a fast hitting task. They also showed that a target that appears to move more quickly than it actually does, because the background is moving in the opposite direction, is hit more quickly than a target on a background that is moving in the same direction as the target (and thus appears to move more slowly). While the perceived velocity of the targets differed, the position of the targets over time did not. Thus, the hand velocity depends on the perceived speed of the target and not on its position.

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A second explanation for speed coupling was suggested by Bairstow (1987). He found that the initial direction of hand movement was only crudely planned for different target speeds. As subjects did not aim further ahead of faster targets, Bairstow claimed that they were obliged to move more quickly to faster targets. Similarly, Smeets and Brenner (1995) proposed that people do not move their hand in a direction that suits the velocity of the target. Instead, they direct their hand as if a certain (mean) speed is expected and update this direction during the movement on the basis of the expected velocity and the perceived target position. During the last 110 ms of the movement, they are unable to update their action because of the time it takes to process visual information on target position and to transpose it into motor action (Brenner and Smeets 1996). To avoid arriving in front of the target when it moves slower than expected and behind it when it moves faster, people adjust the velocity of the hand to that of the target: they move faster to fast objects than to slow ones. In this way they compensate for the systematic error caused by moving their hand along an inappropriate path.

In the present study, we will examine whether subjects indeed adjust hand velocity to target velocity in order to compensate for the error in hand path, as proposed by Brenner and Smeets (1996). The hypothesis predicts that there are two situations in which speed coupling is not necessary to intercept the target. First, if the hand's path is appropriate for the target velocity: If the target moves at the expected velocity there will be no systematic errors that need to be compensated for. Second, if the accuracy demands are low: Subjects should be free to hit slow targets as quickly as fast ones because, despite systematic errors due to the visuomotor delay, they will hit the targets anyway. In the following, we will test whether speed coupling indeed disappears in these two situations.

The same experimental setup was used as by Brenner et al. (1998). Subjects hit simulated spiders with a rod. The spiders ran from left to right over a screen. Three conditions were presented to the subjects. In the control condition the target velocities varied randomly. To make subjects expect the correct velocity, so that they could optimize the direction in which they moved their hand, we presented blocks of consecutive spiders running at the same velocity in the so-called predictable condition. In order to decrease accuracy demands, subjects used a rod with a tip that was sufficiently large to make speed coupling superfluous (large-tip condition). Our hypothesis is that there will only be speed coupling in the control condition.

Materials and methods

The setup was designed to allow subjects to behave as freely and naturally as possible, while meeting the experimental requirements. A schematic view is shown in Fig. 1.

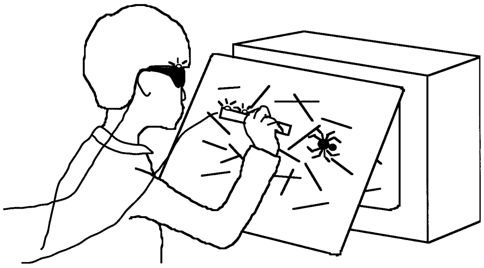

Fig. 1 A schematic view of the experimental setup. The subject sat in front of a monitor on which the stimuli were presented. Shutter glasses made the stimuli appear on a protective screen. IREDs were attached to the hitting rod and the glasses so that the position of the head and the rod could be determined

Subjects used a 22-cm-long Perspex rod to hit simulated spiders that were running across a background. By having the subjects wear liquid-crystal shutter spectacles and presenting different images to the two eyes, the spiders were made to appear three-dimensional and the background appeared to be situated on a transparent Macrolon screen (Lexan). The screen was placed in front of the monitor to protect it from the impact of the rod, and it was tilted 30° backwards to let the subjects hit more comfortably.

The radius of the hitting rod was 0.9 cm. It was held between the fingers and thumb like a pen. Typically, the tip of the rod was about 1 cm from the fingertips. In the large-tip condition, a rubber disc with a radius of 2.7 cm was attached to the tip of the rod. As will be explained in the following, this was expected to be large enough to make speed coupling unnecessary. Spiders ran at 6 cm/s, 12 cm/s or 18 cm/s. As subjects cannot adjust the direction of their hand during the last 110 ms of the movement because of the visuomotor delay, guiding the hand on the basis of the mean velocity rather than the current velocity would give rise to an error of 0.66 cm whenever the spider moved 6 cm/s slower or faster than the mean speed of 12 cm/s. This is the systematic error that the speed coupling is supposed to compensate for. In Brenner et al. (1998) the distribution of hits relative to the spiders was approximately 5.5 cm wide. Thus, if subjects do not couple the speed of their hand to that of the target, they make an error of, at most, (5.5 cm/2)+0.66 cm=3.41 cm. Because in the present experiment, the error they were allowed to make with the large-tipped rod was 3.6 cm, they did not need speed coupling to compensate for the error. Moreover, the distribution of hits was expected to be narrower in the present study because, in the former, the spiders' velocity sometimes changed unexpectedly.

The spider was yellow, with legs that moved as a real spider's would. Its body and head together were 0.8 cm long; including the legs its length was approximately 1.8 cm. The spider always started 8 cm to the left of the rod, as we learned from earlier experiments that this results in hand paths that are, on average, perpendicular to the screen. It moved to the right across a background of 4-cm red lines. The lines were placed randomly within 15 cm of the center of the transparent screen and their intensity faded at the edges. A new background was generated for each trial.

Three infrared markers (IREDs) were attached to the shutter spectacles and two to the rod; one at the end furthest from the tip, and one 6.5 cm from the end. A movement analysis system (Optotrak 3010; Northern Digital) recorded the positions of the IREDs at 250 Hz. The recorded positions were not only necessary to answer the experimental questions but also used on-line to guide the experiment.

Information was needed about when and where the screen was hit, so that feedback could be given. If the spider was hit (if the center of the rod came within 1.8 cm of the center of the spider; or within 3.6 cm for the large tip) it looked crushed; if the subject missed the spider, the latter ran away in the opposite direction from the rod.

Information about the position of the rod was also necessary to help the subjects start with the rod in the right place, which was defined as somewhere within 5 cm of a certain position in space.

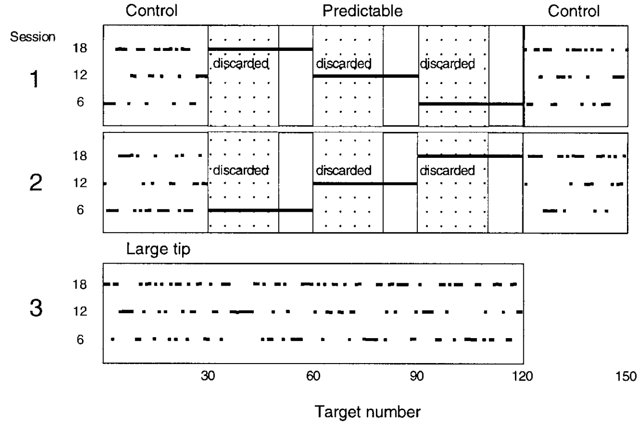

Fig. 2 An overview of the design. There were three experimental sessions, with spiders running at three different velocities (6 cm/s, 12 cm/s, and 18 cm/s). In each of the first two sessions, subjects used the normal hitting rod to hit the spiders. Each of these sessions consisted of parts in which the target velocity was expected and parts in which it was not (*Control*). In the third session, subjects used the rod with the large tip

This position was about 45 cm horizontally away from the center of the protective screen. The subject was allowed to sit any way he or she wanted. Directions were given about where to hold the rod by means of written instructions on the screen (for instance, “further to the left”) and a green line, which pointed out of the screen in the direction in which the rod had to be held. The next trial did not begin until the hand was in the required position.

Information about the position of the subjects’ eyes was needed to guide compensation for motion parallax when the subject moved his head (because the virtual objects are nearer than their images on the computer screen). Note that, from the position of the shutter spectacles, only the positions of the eyes in space were derived, not their orientation in the head. The delay in adapting the stimuli to the subjects’ movements was 21±3 ms.

Design

An outline of the experimental design is given in Fig. 2. Data were collected in three conditions, which were presented during three sessions, with intervals of 3 h to 10 days between them. In each of the first two sessions, 150 spiders were presented in five blocks of 30 trials. During the first and the last block, targets moving at three different velocities (6 cm/s, 12 cm/s, and 18 cm/s) were presented in random order (control condition). Within each of the other three blocks, all targets moved at the same velocity (predictable condition). By the end of these blocks, the subjects’ expectation of the velocity of the next target should be correct. To account for practice and fatigue, each subject performed the whole series twice; in one session the three middle blocks were presented in the order 6 cm/s, 12 cm/s and 18 cm/s, and in the other session the order was reversed. Half of the subjects performed one order first and the other half performed the other order first.

In the third session, the large-tipped rod was used to hit 120 spiders, 40 per velocity (6 cm/s, 12 cm/s and 18 cm/s), in random order (large-tip condition).

Subjects and instruction

Ten volunteers from our department participated in the experiment. They all hit with their right hand. Before every session, the subjects were instructed to hit the spiders with the rod as soon as they appeared and as quickly as possible. They were not told about the existence of the blocks in the first two sessions, but in the third session we drew their attention to the enlarged tip.

Analysis

For the predictable condition, we only analyzed the last ten trials of each block. We assumed that after being presented with 20 spiders running at the same speed subjects expect the correct target velocity. Fifteen of the 3000 trials were excluded from analysis for technical reasons. Another four were removed because subjects missed the center of the spider by more than 4 cm with the normal-sized rod.

For each trial, a number of measures were defined. Reaction time is the time at which the speed of the hand exceeds 0.1 m/s. The initial hitting direction is the angle between the shortest horizontal line from the starting position of the hand to the screen and the line from the starting position to the location of the hand when it had moved 5 cm closer to the screen. The lateral hit error is the distance from the center of the spider to the position of the hit, in a lateral direction (i.e., in the direction in which the spider was moving). If the subject hit behind the center of the spider, a negative value was assigned to the lateral hit error; if he hit in front of it, the value was positive. Note that one can make twice as large an error in the large-tip condition as compared to the other two conditions and still hit the spider! To represent the speed of the hand, we chose the maximal hand velocity in the direction perpendicular to the screen. The theoretical advantage of this measure is that it is insensitive to lateral corrections during the movement. However, the difference with the maximal tangential velocity is very small, because letting the spider start 8 cm to the left from the rod ensured that all the movements were almost perpendicular to the screen. The reason for not using movement time is that this measure is rather sensitive to the definition of movement onset.

Beside the measures already discussed, which were determined for individual trials, we determined two measures per condition for each subject. The first reflects the extent to which subjects hit fast spiders quicker than slow ones. To compute this “strength of speed coupling,” we subtracted the mean maximal hand velocity toward slow spiders from that toward fast spiders and divided this by the mean maximal hand velocity toward spiders running at the mean velocity (12 cm/s). The second measure is the variable error, which was determined separately not only for each condition and each subject but also for each spider velocity. We defined it as the standard deviation of where subjects hit relative to the spider. Consequently, both the error in horizontal (lateral) direction and in vertical direction are considered in this measure.

All results were evaluated using paired *t*-tests. We took $P<0.05$ as the level of significance.

Results

Reaction time

The mean reaction time per spider velocity and condition is shown in Fig. 3A. As already found by others (Savelsbergh et al. 1992; van Donkelaar et al. 1992; Smeets and Brenner 1995), subjects reacted quicker when the target moves faster (for an explanation, see Smeets and Brenner 1994). Moreover, the overall mean reaction time was significantly shorter in the large-tip condition than in the control ($t_{29}=-8.18$, $P<0.01$).

Initial hitting direction

As is shown in Fig. 3B, subjects take more consideration of the target’s velocity when initiating their movements

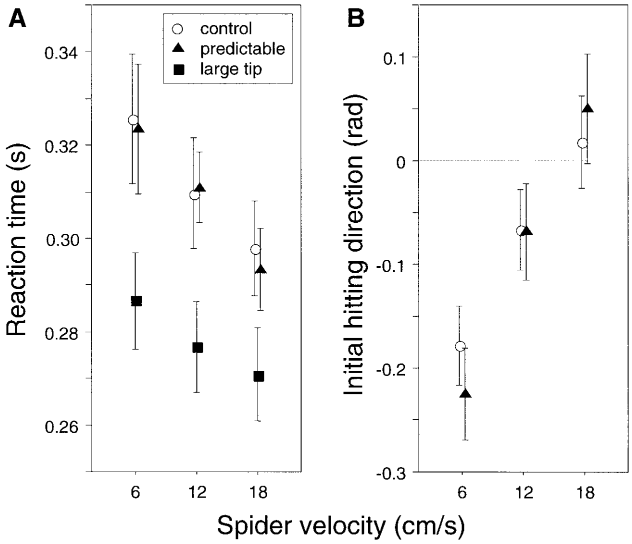

Fig. 3A,B Reaction time and initial hitting direction. *Error bars* represent the standard error between subjects. **A** Reaction time per spider velocity and per condition. Reaction time decreases with target velocity. **B** Initial hitting direction per spider velocity in the control and the predictable condition. The higher the value, the more to the right the subject started to move. In the predictable condition, initial hitting direction differs significantly more between slow and fast spiders than in the control condition. The initial hitting direction in the large-tip condition is not shown here, because it cannot be compared directly with the other conditions owing to differences in reaction time

in the predictable condition, where that velocity is expected, than in the control condition. In the predictable condition, the hand started to move more to the left when a slow spider was presented (low value of hitting direction) and more to the right when a fast spider was presented (high value). The difference in hitting direction between the fast and the slow spider is significantly larger in the predictable than in the control condition (t_9=–3.97, P<0.01). As Fig. 3A shows, this cannot be attributed to differences in reaction time.

Maximal hand velocity and speed coupling

In Fig. 4A maximal hand velocities are shown for each spider velocity and each condition. The maximal hand velocity differs between conditions: subjects clearly hit fastest in the large-tip condition. They also clearly hit fast targets more quickly than slow ones in every condition.

In Fig. 4B the strength of speed coupling is shown for each condition. Speed coupling was strongest in the control condition (about 13%) but it did not disappear in the other cases; a one-sample *t*-test showed that, in both the predictable and the large-tip condition, speed coupling differed significantly from zero, with t_9=2.67 and t_9=2.77, respectively (both P<0.05). Thus, contrary to our expectations, maximal hand velocity still depended on target speed.

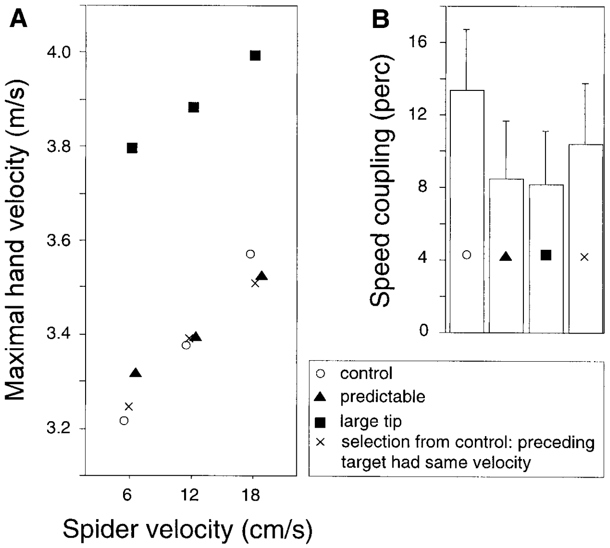

Fig. 4A,B Maximal hand velocity and speed coupling. The *crosses* represent selected data from the control condition: they indicate the mean maximal velocity toward spiders that were preceded by a spider moving at the same velocity. **A** Maximal hand velocity for each spider velocity and each condition. Subjects move fastest in the large-tip condition. Maximal velocity depends most strongly on target velocity in the control condition, but speed coupling is also present in the other two conditions. **B** Strength of speed coupling for each condition and the selection from the control condition. *Error bars* show the standard error across subjects. The speed coupling is strongest in the control condition, but did not disappear in the other two conditions. About half of the difference between the predictable and control condition is reached if only the preceding spider moves at the same velocity as the present one

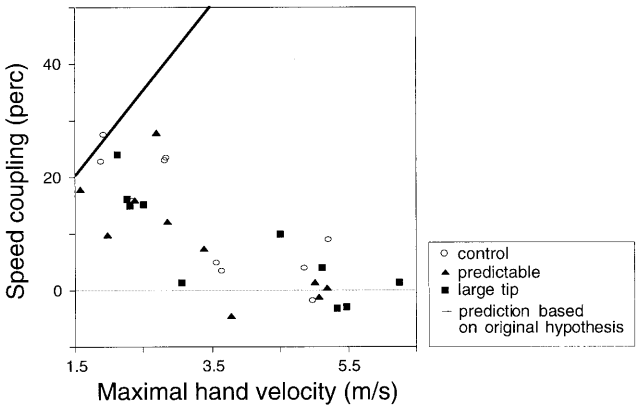

Fig. 5 Negative correlation between strength of speed coupling and maximal hand velocity (R^2=0.7). Every subject is represented by one point for each condition, i.e., three points per subject. The *line* depicts the relation between the maximal hand velocity and strength of speed coupling predicted on the basis of our original hypothesis (see also Brenner and Smeets 1996 and Discussion)

Speed coupling significantly weakened in the large-tip condition (paired *t*-test between large-tip and control condition: t_9=–4.08, P<0.01), which is in line with our hypothesis. However, we do not think that this is a direct effect of the decreased accuracy demands. As is shown in Fig. 5, the strength of speed coupling correlates nega-

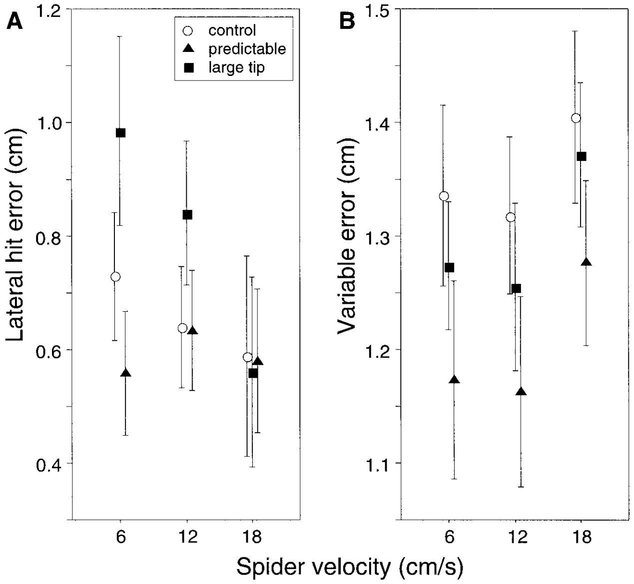

Fig. 6A,B Hit error per spider velocity in the three conditions. *Error bars* represent standard errors between subjects. **A** Systematic error. Only the lateral direction of the errors is considered. The center of the spider is located at zero; positive values indicate a bias toward hitting in front of the spider. The error seems to depend on target velocity. This dependency is strongest in the large tip and weakest in the predictable condition, Note that spiders are considered hit if the error is smaller than 1.8 cm in the predictable and control condition and smaller than 3.6 cm in the large-tip condition. **B** Variable error. Variable error is highest in the control condition, and lowest in the predictable condition. It is also higher for fast spiders

tively with maximal hand velocity (R^2=0.7 for a linear regression, with a slope of –6.0; maximal hand velocity averaged over all target speeds). A high hand velocity (as observed in the large-tip condition) is associated with a weak speed coupling. Thus the low speed coupling is probably the result of faster movements rather than of less required accuracy.

As can be seen in Figs. 3B and 4A, there are differences between the control and the predictable condition in maximal hand velocity and initial hitting direction per spider velocity. Plots of these two variables as a function of trial number (not shown) suggest that the change at the onset of each block in the predictable condition occurs within a few trials. This raised the possibility that the subjects' expectation was largely based on the directly preceding trials. To investigate this further, we examined the influence of the velocity of the preceding trial in the control condition. We compared trials from the control condition, which were preceded by trials with the same target velocity (crosses in Fig. 4), with trials from the predictable condition. It appears that a considerable part of the difference in strength of speed coupling between the predictable and the control condition can be attributed to the velocity of the directly preceding spider.

Systematic error

Figure 6A shows the mean lateral hit error per spider velocity and per condition. The mean hit error is always larger than zero, i.e., the spider is hit in front of its center. As predicted, subjects make systematic errors in the large-tip condition; they hit significantly further in front of slow targets than fast targets (t_9=2.50, P<0.05). A similar tendency is observed in the control condition, though this is not significant (t_9=1.09). In the predictable condition the bias is not present at all (in accordance with the hypothesis).

Variable error

The variable error is presented in Fig. 6B. The variability is largest in the control condition (not in the large-tip condition!), and smallest in the predictable condition. Variable error is significantly larger for fast spiders than for slow or intermediate spiders (t_{29}=–2.50 and t_{29}=–2.53, respectively, in both cases P<0.05).

The combination of systematic and variable errors resulted in 78% of the spiders being hit in the control condition, 84% in the predictable condition, and 99% in the large-tip condition.

Discussion

We predicted that speed coupling would disappear if subjects expected the spiders to move at the velocity that they subsequently moved or if they no longer had to hit accurately. Although in both the predictable and the large-tip condition speed coupling was weaker than in the control condition, it did not disappear in either of them. In the large-tip condition, subjects may still have hit fast spiders more quickly than slow ones, because they did not "notice" that the task had become easier (despite the instruction) or because they wanted to "keep on the safe side". However, subjects did behave differently using the large-tipped rod; they hit faster and made more systematic errors, so they did not ignore the large tip altogether. Nevertheless, the adjustment could be incomplete.

Assuming that enough trials were presented for the expected target velocity to conform to the presented target velocity, the hypothesis tested in this study cannot explain why the speed coupling did not totally disappear in the predictable condition. The results themselves indicate that 30 trials sufficed to expect the correct velocity. As already mentioned, an important part of the difference between the maximal hand velocity is already achieved when the directly preceding spider runs at the same velocity as the current one. Apparently, subjects base their expectation of the velocity of the up-coming target largely on that of the preceding one. Furthermore, the lower systematic and variable errors in the predictable condition (Fig. 6) suggest that the predictability is used to reduce the errors. Subjects also differentiate their initial hitting direction more over the three target velocities in this condition (Fig. 3B).

Additional, conclusive evidence that the hypothesis cannot be correct is presented in Fig. 5. The negative correlation between maximal hand velocity and strength of speed coupling is not consistent with the hypothesis; the hypothesis predicts a positive correlation, because subjects who generally move more quickly have to change their hand velocity more to arrive at the screen the same amount of time earlier or later. By using the equations presented by Brenner and Smeets (1996), one can compute an expected relationship between mean maximal hand velocity and strength of speed coupling. Assuming that the expected target velocity was equal to the mean velocity (12 cm/s) and that the hand moved with a constant acceleration, the hypothesis predicts that the data points should follow the line drawn in Fig. 5. They obviously do not.

Subjects generally hit spiders in front of the center, especially in the large-tip condition. Perhaps they try to minimize the time that the spider is occluded by the hand and the hitting rod. This strategy could account for the largest biases being found in the large-tip condition, because the large-tipped rod occludes more of the visual space than the normal rod does. It can also account for the observed dependency on target velocity, slow spiders being hit more at the front than fast ones, because slow spiders are closer to the rod for longer periods of time and are generally hit further to the left side of the screen. Attempts to minimize the time that the target is occluded could thus account for the observed systematic error in the large-tip and control conditions.

While analyzing the results, we thought of a new hypothesis to explain speed coupling. Subjects may move faster to fast targets, because they consider fast targets more likely to get out of reach than slow ones. Though all spiders in our experiment were hit well before they reached the border of the screen, subjects may still have felt that if they did not move quickly fast spiders would move out of reach. We carried out an additional experiment to test this hypothesis. Eleven subjects participated (five of them also took part in the previous experiment). The control condition was repeated, but we added two other types of spiders. Besides spiders that started 8 cm to the left of the rod running at 6 cm/s, 12 cm/s, and 18 cm/s, we presented spiders that started 3 cm to the left of the rod running at 12 cm/s and spiders that started 2 cm to the right of the rod running at 6 cm/s. These spiders were hit, respectively, 4.8 cm and 10.0 cm further to the right than their counterparts starting on the left, so they could be considered more likely to get away. Nevertheless, subjects did not hit them significantly faster (t_{10}=–0.99 for the slow spiders; t_{10}=–1.71 for the intermediate spiders). We conclude that, at least in our experiment, speed coupling is not caused by the impression that fast targets are more likely to move out of reach.

This experiment also provided additional evidence, besides that given in the introduction, that speed coupling is not caused by moving faster toward targets on the right (in ipsilateral space). The fast spiders were hit quicker than the slow spiders starting on the right, although the latter were hit 4.2 cm to the right of the former.

New hypothesis

Three attempts to explain the fact that people hit fast targets quicker than slow ones are rejected. These are the idea that subjects feel that the fast targets get away if they do not hit quickly, the idea that it is because one can move quicker in ipsilateral than in contralateral space, and the idea that you need to adapt the hand velocity to target velocity to account for not adjusting the hand's path to the target's velocity. We here propose a new function for speed coupling.

In order to successfully hit a moving target, both the position and the time you arrive at that position must be planned correctly. Of course, positioning and timing have to suit each other. The critical issue for our new proposal is that errors in positioning and timing are not equally important in intercepting fast and slow objects. An error in timing is far more troublesome when intercepting fast targets than when intercepting slow ones, because fast targets move a larger distance in the time that you arrive too early or too late.

Our proposal is that subjects move more quickly to improve their timing. If subjects move quickly, an error in the estimated distance to the screen will lead to smaller deviations of the estimated time of arrival. Moreover, the timing of quick movements tends to be more reproducible (smaller standard errors for quicker movements; Wallace et al. 1990) so that subjects may arrive closer to the estimated time. In an interception task, Schmidt (1969) found that an increase in movement time is accompanied by a decrease in timing accuracy. According to Schmidt, this is caused by subjects making larger errors in estimating longer movement times.

These advantages of moving quickly compete with the well-established finding that moving slowly helps to reach a planned position accurately (Fitts and Peterson 1964). Thus, the speed-accuracy tradeoff depends on the velocity of the target. For fast targets, the optimal velocity is higher than for slow targets.

An important difference between the original hypothesis and the hypothesis just described is the kind of error that is assumed to be diminished by speed coupling. According to the original hypothesis, the goal of speed coupling is to reduce the systematic bias in order to prevent hitting behind or in front of the target. In contrast, the newly proposed hypothesis for the origin of speed coupling is that it minimizes the variable error.

The fact that the variable error is not smallest in the control condition seems to contradict the new hypothesis; in the control condition, speed coupling is strongest, so one would expect the variable error to be smallest. However, in the predictable condition, subjects use knowledge about the velocity of the up-coming spider, so they do not have to correct the movement much on the way. This presumably reduces the variability. Similarly, in the large-tip condition, subjects appear to make larger systematic errors (see Fig. 6A) rather than correcting the hand's path. Presumably, corrections to the hand's path are responsible for much of the variability and such corrections are most prominent in the control condition. Further research is required to determine the validity of the new hypothesis.

Acknowledgements This research was supported by NW0 (MAG) grant 575–23 015.

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