Exp Brain Res (2005) 165: 28–36
DOI 10.1007/s00221-005-2277-y

RESEARCH ARTICLE

Anne-Marie Brouwer · Jeroen B. J. Smeets · Eli Brenner

Hitting moving targets: effects of target speed and dimensions on movement time

Received: 3 September 2004 / Accepted: 28 January 2005 / Published online: 3 May 2005

Abstract To hit moving targets, one not only has to arrive at the right place but also at the right time. Moving quickly reduces spatial precision but increases temporal precision. This may explain why people usually move more quickly toward fast targets than toward slow ones, because arriving at the right time is more important when hitting fast targets. The temporal accuracy required depends not only on the target's speed but also on its length in the direction of motion; it decreases with increasing length. Here we investigate the effects of variations in the target's speed and dimensions on the subject's movement time. We asked subjects to hit targets that moved from left to right as quickly as possible with their index finger. The targets varied in length in the direction of motion (width: affecting both spatial and temporal demands), in length in the orthogonal direction (height: affecting spatial demand), and in speed (affecting temporal demand). Targets were presented in random order during one session and in blocks of trials with identical targets during another session. In the latter session subjects could optimize their strategy for each target separately. In the random condition subjects hit fast targets more quickly than slow ones. Their movement time was also affected by the target's size (the spatial demand), but not by the direction of the elongation. For the blocked condition, subjects did consider the direction of the elongation. We conclude that people do not consider an object's orientation to estimate the temporal demands of an interception task, but that they use the object's size and speed, and their experience from previous trials.

Keywords Aimed movement · Visuomotor control · Interception · Timing · Movement accuracy

A.-M. Brouwer (✉)
Max Planck Institute for Biological Cybernetics,
P.O. Box 2169, 72021 Tübingen, Germany
E-mail: anne-marie.brouwer@tuebingen.mpg.de
Tel.: +49-7071-601642
Fax: +49-7071-601616

J. B. J. Smeets · E. Brenner
Department of Neuroscience,
Erasmus Medical Center, Erasmus University,
P.O. Box 1738, 3000
DR Rotterdam, The Netherlands

Introduction

To hit a stationary target, you have to plan where your hand (or other hitting device) should arrive. To hit a moving target, not only the position, but also the moment of arrival at that position must be planned. Good temporal accuracy [1] is especially important for hitting fast targets. If you arrive a bit later than you had planned, you may still hit a slow target but a fast target will already have left the location that you hit.

Several studies show that moving rapidly improves temporal accuracy. Newell et al. (1979) asked their subjects to move a handle across a certain distance in a time that was as close as possible to a given movement time. The subjects' absolute and variable timing errors both decreased with decreasing target movement time and increasing movement speed. In a study by Schmidt (1969), subjects hit targets by moving a bat along a rail. The targets were moved by a belt that was oriented perpendicularly to the rail. Here too, timing error decreased with decreasing movement time. Using a similar task to that in Schmidt (1969), Tresilian and colleagues reported smaller standard deviations for shorter movement times (Tresilian and Lonergan 2002; Tresilian et al. 2003). Several possible reasons for increased temporal accuracy for fast movements have been proposed, and they may all contribute to improved timing with faster movements. According to Schmidt (1969), subjects simply make larger errors in estimating longer

[1]Throughout the whole paper, "accuracy" can be read as "accuracy and precision", i.e. both a correct average value and low variability.

movement times. Brouwer et al. (2000) suggest that the effect of an error in estimating the distance across which one wants to move on the planned time of arrival is smaller if the movement is quick. Newell et al. (1979) explain the effect in neuromuscular terms. Finally, there is the fact that there is a natural limit to moving faster but not to moving slower. Movement time distributions are skewed, with a clearer cut-off for short movement times than for long ones. This sharp cut-off could help to make movement times less variable if one always tries to move as fast as possible.

Besides improving temporal accuracy, it is well known that moving quickly reduces spatial accuracy (Fitts and Peterson 1964). Possible reasons for this effect are signal dependent noise in the motor system (Harris and Wolpert 1998) and the decreasing possibility of correcting the movement by using visual feedback (Tresilian et al. 2004). For hitting moving targets, the optimum movement speed is thus determined by a balance between the need for temporal accuracy, reinforcing fast movements, and the need for spatial accuracy, reinforcing slow movements. Many studies about intercepting moving targets show that people hit fast targets more quickly than slow ones (e.g. Carnahan and McFayden 1996; Fayt et al. 1997; Savelsbergh et al. 1992; Van Donkelaar et al. 1992) even if explicitly asked always to move as quickly as possible (Brouwer et al. 2000, 2002, 2003; Smeets and Brenner 1995). The combination of greater required temporal accuracy for fast targets than for slow ones, and the improved timing for fast movements, is suggested as the reason for this speed coupling (Brenner et al. 2002; Brouwer et al. 2000; Caljouw et al. 2004; Tresilian and Lonergan 2002). According to this view, the movement speed is adjusted to the required temporal accuracy, rather than directly to the speed of the target (which obviously influences the required temporal accuracy).

The temporal accuracy required depends not only on the target's speed but also on the target's length in the direction of its motion. If a target is long in its direction of motion, the time at which one arrives at the hitting position is less critical than if it is short: if one arrives at a certain position later than planned, there is a bigger chance of still hitting a long target than a short one. Similarly, when hitting moving targets with a bat, the temporal required accuracy decreases with increasing size of the bat. Tresilian and Lonergan (2002) asked subjects to hit targets using a bat that could be moved along a rail. The targets moved along a track that was perpendicular to the rail. The temporal accuracy required was manipulated by systematically varying the target's speed and size, and the size of the bat. Tresilian and Lonergan (2002) quantified the required temporal accuracy by determining a critical time window. This is the time within which contact with the target was possible: the sum of the length of the bat and the target, divided by the target's speed. As expected, movement time decreased with a decreasing time window. However, varying the time window by manipulating the target's speed had a larger effect on the movement time than doing so by manipulating the size of the target or of the bat. The greater effect of target speed than target size was replicated in a study by Tresilian et al. (2003). Thus it would seem that it is not just the high temporal accuracy required that makes subjects move quickly to fast targets.

Because subjects in the studies by Tresilian and colleagues moved the bat along a rail, they could only (or only needed to) plan their timing. In a more recent experiment (Tresilian et al. 2004) the setup was modified to enable subjects to move freely in the vertical direction (which was perpendicular to the target's motion), to investigate how target size (height) affects the speed of hitting moving objects. However, subjects were still restrained in the moment and the horizontal location at which the target could be hit. This was possibly the reason for a lack of correlation between movement speed and spatial variability and (thus) a lack of effect of target size on hitting speed. We are interested in how subjects' movement times are affected by different target speeds and dimensions if subjects are allowed to move freely and have to determine both when and where they will hit the moving targets.

Figure 1 depicts our setup, showing what we mean by the width and height of the target, and by the horizontal and vertical directions. We asked subjects to hit targets that moved from the left to the right as quickly as possible. The targets varied in height and width. Varying the height only affects the required spatial accuracy—the vertical component of the movement endpoint has to be more accurate to hit a short target than to hit a tall one [2]. Varying the width affects both the required temporal and spatial accuracy: both the horizontal component of the movement endpoint and the moment that one reaches that point have to be more accurate to hit a narrow target than to hit a wide target. Independently varying the height and width resulted in four targets: a small square, a large square, a rectangle oriented in the horizontal direction (i.e. in the direction of the target's motion) and an identical rectangle oriented in the vertical direction. We also varied the speed. Doing so only affects the temporal accuracy required: one has to be more accurate in time to hit a fast target than to hit a slow one. We expected subjects to move particularly quickly to tall and fast targets, because for such targets the spatial accuracy is likely to be less important than the temporal accuracy. We expected subjects to move particularly slowly to short and slow targets, because then the spatial accuracy is likely to be more important than the temporal accuracy. For the different target widths, the optimum movement time will be a compromise between the importance of achieving good timing (demanding fast movements) and the importance of achieving good spatial accuracy (demanding slow movements). If

[2] We only consider the temporal and spatial errors of the movement endpoint, irrespective of their causes (van Beers et al. 2004).

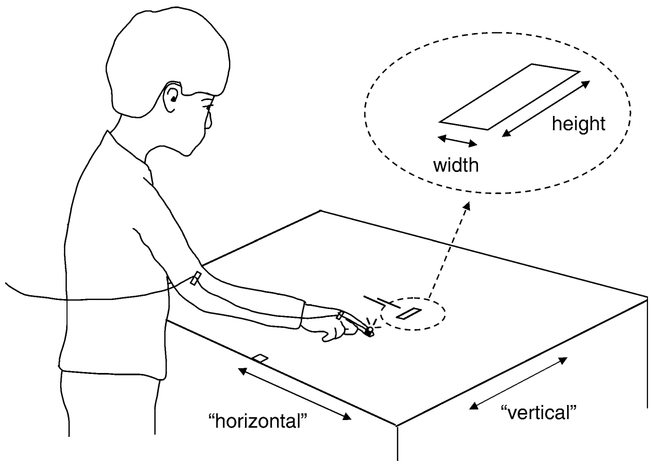

Fig. 1 Schematic view of the setup

subjects only respond to varying width because it affects the spatial accuracy required, we expect to find a similar increase in the subjects’ movement time when we reduce the height as when we reduce the width. If subjects take into account that differences in target width also affect the temporal accuracy required, we expect the increase in movement time to be less prominent when the width is reduced than when the height is reduced. If so, horizontally oriented rectangles will be hit differently from vertically oriented rectangles. In one session we presented different kinds of target in a random order and in another we presented them as blocks of identical targets. Under the latter conditions, subjects knew which target to expect and were therefore able to optimize their strategy for each kind of target separately. Previous studies about hitting moving targets have shown that subjects are strongly influenced by the target presented in the previous trial (Brouwer et al. 2000; De Lussanet et al. 2001). Thus, the results under the blocked conditions can be used to determine whether our manipulations could be expected to have measurable effects.

Methods

Materials

A schematic depiction of the setup is shown in Fig. 1. Subjects stood in front of a 113 cm×84 cm screen that was tilted 20° relative to the horizontal. A CRT projector (800×600 pixels, 120 Hz) back-projected the stimuli, via a mirror, on to the screen. An infrared light-emitting diode (IRED) was attached to the nail of the subject’s index finger. An Optotrak (Northern Digital) measured this IRED’s changing position at 750 Hz.

Design

The targets were dark rectangular shapes moving from left to right across a bright yellow background at either 33 or 99 cm s^{-1}. The rectangles’ widths and heights could be 2.08 or 6.24 cm, resulting in a small square, a large square, a rectangle oriented in the direction of its motion, or a rectangle oriented in the direction orthogonal to its motion. In Fig. 1, an example of the last of these (a tall, narrow target) is shown. Following Tresilian and Lonergan (2002), we quantified the required temporal accuracy for each target by calculating the amount of time it could be hit at one particular position. We refer to this as the time window. It is the target’s width divided by the target’s speed. The feedback is based on whether the IRED on the fingertip is within the target. Table 1 shows the time windows for each target width at each speed.

To start a trial the subject had to place her or his finger at a visually indicated starting position at the lower edge of the screen. After a random time interval (between 600 and 1200 ms) the moving target appeared. The target passed 35 cm from the finger’s starting position in the vertical/sagittal direction. Its starting position was 41 cm to the left of the finger’s starting position for the fast targets and 13 cm to the left for the slow targets. This difference ensured that the hitting positions on the screen were similar for fast and slow targets. Subjects only touched the screen at the start and the end of the hitting movement, but the movement was largely along the screen. Thus, subjects had to decelerate the movement themselves (in contrast with when hitting targets moving on a screen that is perpendicular to the movement). If subjects successfully hit a target (the IRED’s velocity dropped below 10 cm s^{-1} within the target’s boundaries), the target stopped moving and a beep was presented. If subjects missed the target (the IRED’s velocity dropped below 10 cm s^{-1} outside the target’s boundaries), the target moved quickly away from the fingertip (e.g. downward if the subject had hit above the target). If subjects did not stop their finger on the screen at all, the experimental program did not register a hit and a “too late” error message was presented. In that case, the trial was repeated later. Subjects performed trials for 2 target widths×2 target heights×2 target speeds×20 repetitions = 160 trials. First we presented these trials in random order. One or more days later, we presented them to the same subjects in eight blocks, with each block containing 20 identical targets (2 speeds×2 heights×2 widths = 8 blocks, 8 blocks×20

Table 1 Time windows (ms) for each target width and each target speed. The rectangular grey figures indicate the four target shapes

Width (cm) / Speed (cm/s)	2.08	6.24
33	63	189
99	21	63

repetitions = 160 trials). The blocks were presented in a different pseudo random order for each subject.

Subjects and instruction

This experiment is part of an ongoing research program that has been approved by the local ethics committee. Eleven persons volunteered to take part in this study after being informed about what they would be required to do. Three were the authors. The other eight were colleagues from the Erasmus MC, and were naïve about the purpose of the experiment.

We explained the feedback and asked our subjects to hit the targets as quickly as possible with the tip of the index finger of their preferred hand. One of the subjects was left-handed; the others were right-handed. Before the actual experiment started, subjects practised until they were comfortable with the task.

Analysis

We determined the movement time for each trial. This was defined as the time between the moment the velocity of the hand exceeded 10 cm s^{-1} and the moment the downward speed of the hand (in the direction orthogonal to the screen) dropped below 10 cm s^{-1} after the hand had started moving downward to the screen. We also looked at the hand's maximum velocity, but because the pattern of results for this variable was the same as for the movement time (for which we had formulated our predictions), we will not report it here.

We determined the hitting precision in the horizontal direction (i.e. in the direction of the target's movement) and in the vertical direction (i.e. along the screen, orthogonal to the direction of the target's movement) for each subject and each of the eight different target types. We use the standard deviation of the distance between the center of the target and the fingertip at the end of the movement as our measure of variability, and as our measure of its inverse, the precision. The standard deviation was determined separately for the horizontal and vertical directions (SDh and SDv, respectively). A large variability or standard deviation means low precision and vice versa.

From a total of 3520 trials, 44 trials were discarded because of occlusion of the IRED or because the subject started to move within 120 ms of target onset. For the analyses we included both hits and misses. Differences between target types were evaluated by using repeated measures ANOVA with the target's speed, height, and width as factors. We also performed linear regression analysis across subjects and target types to investigate the relationship between movement time and horizontal and vertical spatial variability. We took $P = 0.05$ as the level of significance. All significant effects are mentioned.

Estimating the optimum strategy

We can use our data to estimate the extent to which the movement time affects spatial and temporal precision, and therefore whether (and to what degree) it is advantageous to move rapidly to fast targets. The measured horizontal variability (SDh) consists of both temporal and spatial components. To evaluate the benefit of moving more quickly we must quantify the contribution of each of these sources of variability. To do so we must make some assumptions. We assume that the timing variability is a certain proportion (b) of the movement time (MT). This is justified by the fact that the variability increases proportionally with movement time (e.g. Newell et al. 1979). Variability in timing can be converted into spatial variability by multiplying the timing variability by the speed of the target (b×MT×speed). Because our movements end perpendicular to the screen (see Fig. 2), the variability in the vertical direction (SDv) consists of a spatial component only. If a subject arrives at a certain intended position on the screen at a wrong time, this will result in an error in the horizontal direction but not in an error in the vertical direction because the vertical position of the target does not change over time. The spatial component of the variability in the horizontal direction need not be equal to the variability in the vertical direction, but we assume that it is proportional to it (a×SDv). Combining these variabilities we get the following equation for the total squared variability in the horizontal direction:

$$\mathrm{SDh}^2 = (\mathrm{a}^*\mathrm{SDv})^2 + (\mathrm{b}^*\mathrm{MT}^*\mathrm{speed})^2$$

We used this equation to calculate the values of a and b. Substituting the measured values of the SDh, SDv, and MT for each target speed gives us two equations (one for each speed) with two unknowns (a and b). We could therefore calculate a and b separately for the random and the blocked conditions. A positive value of b would indicate that the timing precision decreases with movement time, as is to be expected from previous studies (e.g. Newell et al. 1979; Schmidt 1969). A high value would indicate a large effect.

Results

For an impression of the kind of movements that subjects were making, we show a top view (upper graph) and a side view (middle graph) of the hand's trajectory in six arbitrary trials by an arbitrary subject (Fig. 2). The accompanying velocity profiles are shown in the bottom graph.

Random condition

The graphs on the left in Fig. 3 show the average movement time for each target in the random condition, plotted as a function of time window (top) and as a

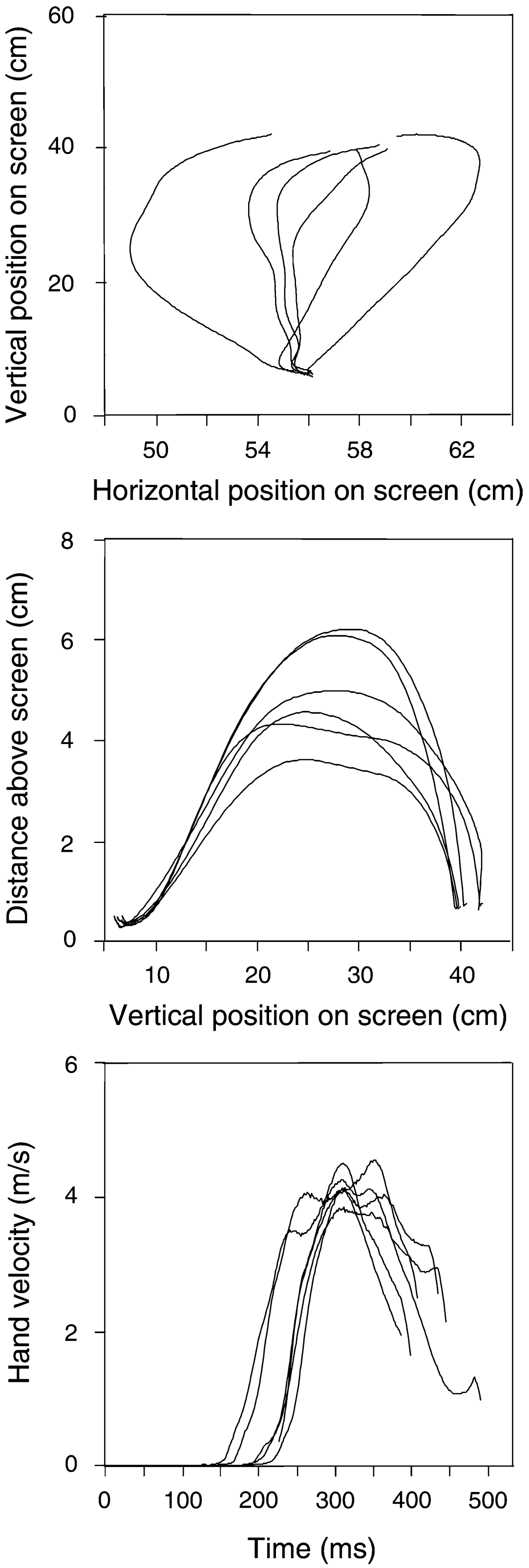

Fig. 2 The hand's trajectory in six arbitrary trials by one of the subjects. The *upper graph* shows the trajectories as seen from above and the *middle graph* shows a side view. The *lower graph* shows the velocity profiles. The data are shown from the moment the stimulus appeared until the end of the hitting movement

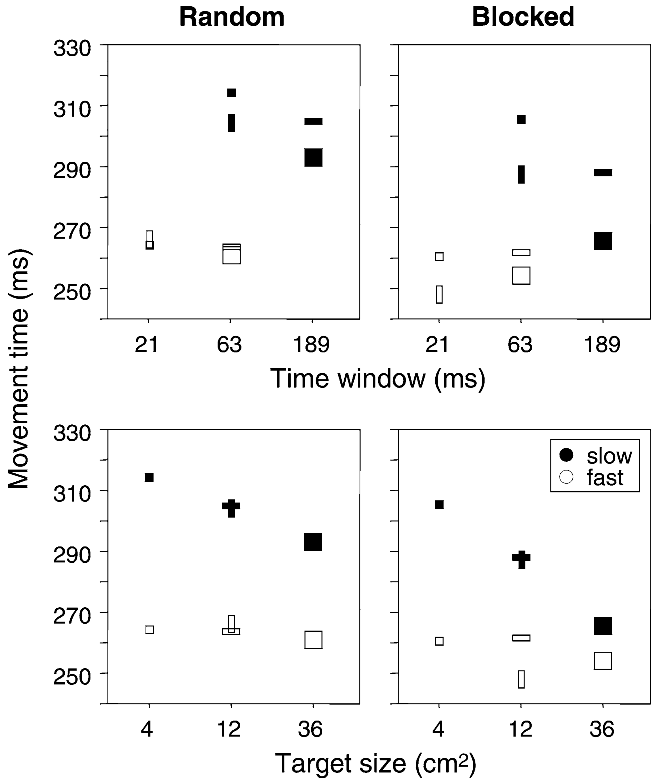

Fig. 3 Movement time for each target in the random condition (*left*) and blocked condition (*right*) as a function of time window (*top*) and as a function of target size (*bottom*). The symbols' shapes match those of the targets. *Filled symbols* are for slow targets and *open symbols* for fast targets

function of target size (bottom). It is clear that movement time is best described as a function of target size and speed rather than time window. A repeated measures ANOVA on movement time indicated there was a significant effect of target speed ($F_{(1,10)}=24.67$, $P<0.01$), with shorter movement times for fast targets than for slow ones (speed coupling). Additionally, width and height both affected the movement time, with shorter movement times for larger targets ($F_{(1,10)}=9.64$, $P=0.01$ for width and $F_{(1,10)}=17.90$, $P<0.01$ for height). On average, the movement time was 7 ms shorter when hitting a wide target than when hitting a narrow one. The movement time was 5 ms shorter when hitting a tall target than when hitting a short one. Both width and height also interacted with speed in the same way: the effect of size was stronger for slow than for fast targets ($F_{(1,10)}=6.44$, $P=0.03$ for speed×width and $F_{(1,10)}=13.04$, $P<0.01$ for speed×height). Thus, variations in target width and height influenced the movement time in the same manner.

The graphs on the left in Fig. 4 show the SDh (top) and the SDv (bottom) in the random condition, plotted as a function of target size. Target speed affected the variability in both directions ($F_{(1,10)}=172.20$, $P<0.01$ for SDh and $F_{(1,10)}=51.12$, $P<0.01$ for SDv) with the standard deviation being larger for fast than for slow

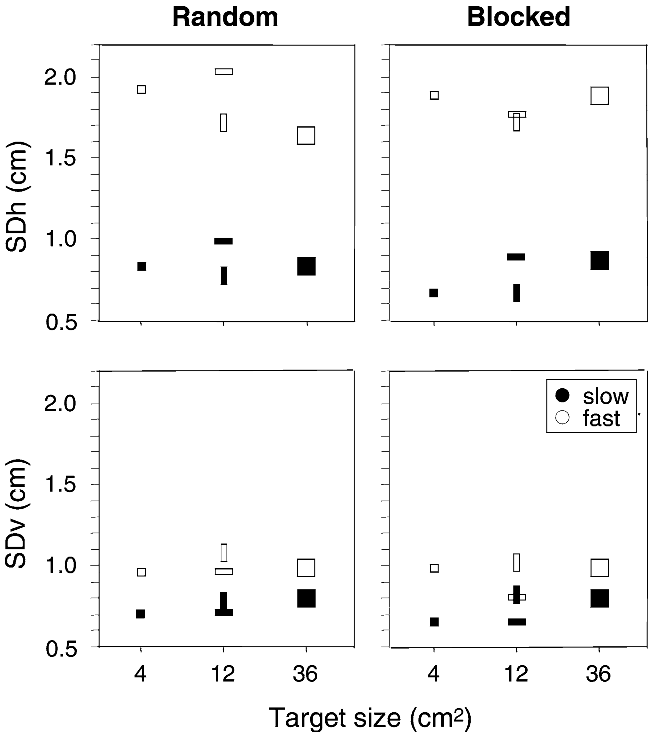

Fig. 4 Standard deviation of the distance between the center of the target and of the fingertip at the end of the movement, as a function of target size. Deviations are in the horizontal (SDh, *top*) and vertical (SDv, *bottom*) directions, for the random (*left*) and blocked (*right*) conditions. The symbols' shapes match those of the targets. *Filled symbols* are for slow targets and *open symbols* for fast targets

targets. Additionally, SDv was larger for the tall than for the short targets (effect of height: $F_{(1,10)} = 12.18$, $P < 0.01$), although the difference was only 0.08 cm. There was no significant effect of width on either measure of precision.

Linear regression analysis across subjects and target types indicated that moving quickly reduced spatial precision. The precision in both the horizontal and the vertical directions depended significantly on the movement time (P-values < 0.01, R^2 values of 0.16 for the correlation between movement time and SDh, and 0.37 for the correlation between movement time and SDv).

Blocked condition

The graphs on the right in Fig. 3 show the average movement time for each target in the blocked condition, plotted as a function of time window (top) and as a function of target size (bottom). The results are similar to those in the random condition, except that the orientation of the elongated targets now did matter. As in the random condition, we found speed coupling as indicated by a significant effect of the target's speed ($F_{(1,10)} = 10.07$, $P < 0.01$). Subjects hit tall targets faster than short ones ($F_{(1,10)} = 10.92$, $P < 0.01$ for movement time) but there was no main effect of width any more. There was an interaction between speed and width ($F_{(1,10)} = 8.22$, $P = 0.02$), indicating that wide targets were hit faster than narrow ones when they were slow, but not when they were fast. In the latter case, there was even an opposite trend. On average, subjects hit tall targets 15 ms faster than short ones. This difference was three times larger than in the random condition. In contrast to the random condition, we did not find an interaction between speed and height.

The graphs on the right in Fig. 4 show the SDh (top) and the SDv (bottom) in the blocked condition, plotted as a function of target size. The pattern of significant effects of the independent variables on these measures was exactly the same as in the random condition. Subjects were less precise in both directions for fast than for slow targets ($F_{(1,10)} = 96.31$, $P < 0.01$ for SDh and $F_{(1,10)} = 13.69$, $P < 0.01$ for SDv). Also, SDv was again larger for tall than for short targets ($F_{(1,10)} = 23.00$, $P < 0.01$). The average effect of height on SDv was 0.13 cm (almost twice as large as in the random condition). Again, there was no significant effect of width on either measure of precision.

As in the random condition, linear regression analysis across subjects and target types indicated that moving rapidly reduced the spatial precision (P-values < 0.01, R^2 values of 0.20 for the correlation between movement time and SDh, and 0.42 for the correlation between movement time and SDv).

Estimating the optimum strategy

We computed the values of a and b in our equation using the average measured standard deviations and movement times (as described in "Methods"). The value for a (the estimated spatial variability in the horizontal direction as a proportion of the variability in the vertical direction) was 0.76 for the random condition and 0.59 for the blocked condition, indicating that the spatial variability is larger in the vertical direction than in the horizontal direction. This is not surprising considering that the hand's movement was mainly in the vertical direction. Several studies have shown larger variability along the axis of movement than on the orthogonal axis (e.g. Messier and Kalaska 1997; Van Beers et al. 2004; Vindras and Viviani 1998). Also, in our setup (Fig. 1) the same physical size corresponds to a smaller visual angle in the vertical direction than in the horizontal direction, so some variability in angular localization will result in a larger spatial variability on the screen in the vertical than in the horizontal direction. For b (the variability in timing as a proportion of movement time) the values were 0.06 for the random and 0.07 for the blocked condition. This fact that the value is positive indicates that the temporal accuracy decreases with increasing movement time, as was expected.

With these values we can estimate the optimum movement times for our average subject. Figure 5 shows this for both the random condition (top) and blocked (bottom) conditions. In each graph, the dashed lines

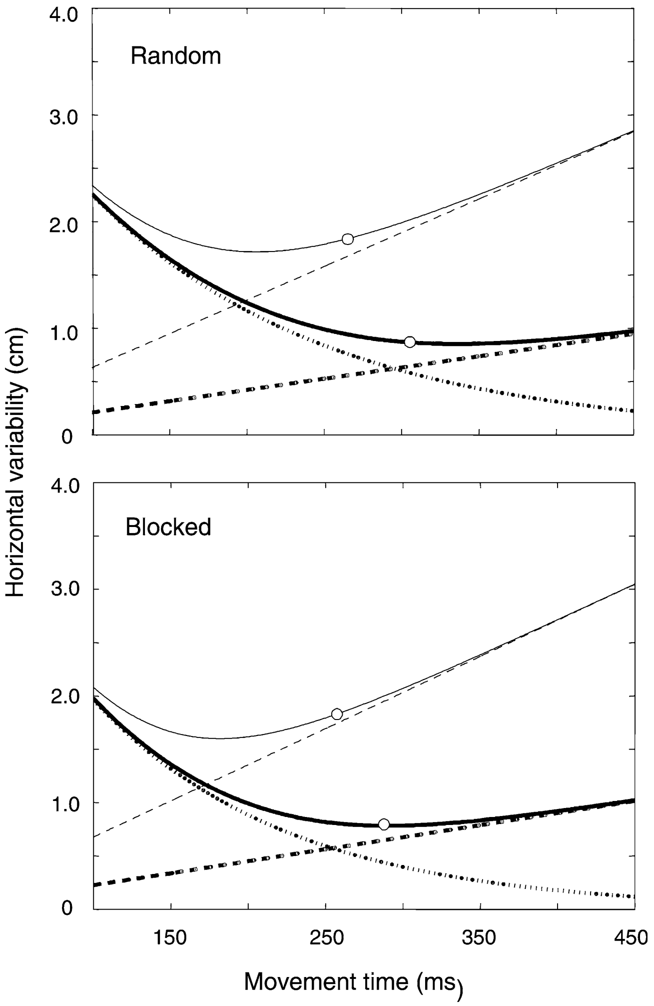

Fig. 5 The effect of movement time on horizontal variability for the random condition (*top*) and the blocked condition (*bottom*). *Thick lines* represent slow targets and *thin lines* represent fast targets. *Dashed lines* indicate the relationship between movement time and timing variability (with timing variability converted into a spatial effect). *Dotted lines* indicate the relationship between movement time and spatial variability. The *solid lines* represent the total horizontal variability, calculated by combining the timing and spatial variability. The *dots* show the average data across all subjects and targets

indicate how the spatial effect of timing variability depends on the movement time, both for slow (thick lines) and fast (thin lines) targets. The dotted curves indicate how the spatial variability depends on the movement time (using the relationship between these two variables as formulated by Fitts and Peterson (1964)). The solid curves indicate the combination of both sources of variability. There is a clear difference between the optimum movement time for slow and fast targets, as illustrated by the different horizontal locations of the minimum in the two solid curves. The dots represent the average MT and horizontal variability as measured in the experiment. For both conditions, the measured horizontal variability is very close to its lowest possible value (i.e. optimum movement time) for slow targets, but the movement time is not optimum for fast targets in either condition. The average absolute difference between the observed and predicted SDh (comparing observed values for each subject and each of the eight different targets with what the solid curves predict) is 0.30 cm in both the random and blocked condition.

Discussion

We investigated how varying a target's speed and dimensions affects the movement time when subjects have to determine both where and when to hit the target. Below, we will discuss the effect of each of these variables on movement time, and then continue to have a closer look at what happened to the precision of the movements.

As has been found many times before, movement time was shorter for fast than for slow targets (speed coupling). This was so both when different targets were presented in random order and when they were presented in blocks of identical targets. Our estimates of the optimum movement time support previous suggestions that speed coupling increases hitting precision (Brenner et al. 2002; Brouwer et al. 2000; Caljouw et al. 2004; Tresilian and Lonergan 2002). According to our estimates, reducing the movement time for fast targets still further, to about 180–200 ms, would have given an even better result (Fig. 5). Subjects may not have done this because of physical limitations, in the sense of not being able to move faster or not wanting to move faster as the impact of the fingertip on the screen gets painful. Our estimate of the amount of increase in timing variability with movement time (7% of the movement time when expressed as the standard deviation) is in good agreement with the literature. In a study by Newell et al. (1979), subjects tried to move a handle a certain distance in a time that was as close as possible to a given movement time. The distances and movement times closest to those in our study are a distance of 15 cm and movement times of 100 and 500 ms. For these conditions, Newell et al. (1979) reported movement time standard deviations of about 9%. In tapping studies, movement time standard deviations of reproduced time intervals were in the order of 5 to 10% (Drewing and Aschersleben 2003; Fetterman and Killeen 1990; Ivry and Hazeltine 1995).

In the random condition, varying width and height affected the movement time in similar ways: tall and wide targets were hit faster than short and narrow ones. Thus, subjects hit larger targets more quickly, but they ignored the direction of the elongation. Different effects of height and width are expected if subjects take into account that variations in the target's height only affect the spatial requirements, whereas variations in the target's width affect both the spatial and the temporal requirements. The results in the blocked condition confirm that our variations in the target's height and width were large enough to affect peoples' performance. In the blocked condition the movement time was always shorter for tall targets than for short, but it was only shorter for wide targets than for narrow when the targets moved slowly. This difference results in a longer movement time for the horizontally oriented fast rectangle than for the vertically oriented fast rectangle (Fig. 3). For fast targets we can expect timing to be critical, and therefore the direction of elongation to matter. Apparently, for slow targets the spatial precision was more important, so the direction of elongation was less relevant. In the blocked condition, subjects optimized their performance for each target separately. They may have done this simply by trial and error, or by taking advantage of the prior knowledge of the type of target that was coming up to program an appropriate movement. Irrespective of how exactly the response to the orientation in the blocked condition came about, we can be sure that subjects were not using information about the target's orientation in the current trial, because there was no (measurable) effect of orientation in the random condition.

The lack of effect of the direction of elongation in the random condition shows that subjects did not take the temporal accuracy required into account. This seems to be in conflict with the conclusions of Trommershäuser et al. (2003a,b) about fast pointing movements toward static targets. They suggest that people directly combine knowledge about their own motor variability with the stimulus properties to plan the optimum movement. In our study, people clearly failed to do so. Thus, the ability of subjects to directly use information to plan an optimum movement is limited. It is possible these limits were more evident in our study because we used moving rather than static targets, which made the task more complicated (see also Landy et al. 2004).

The difference between slow and fast targets is larger in horizontal variability than in vertical variability (Fig. 4). This is because, in contrast with SDv, SDh is not only determined by spatial variability, which becomes larger when subjects move more quickly, but also by temporal variability, leading to large spatial errors if the target moves quickly. The involvement of a spatial component and a temporal component in the horizontal variability is also reflected in the weaker correlation between SDh and movement time compared with that between SDv and movement time. Spatial variability decreases with increasing movement time whereas timing variability increases with increasing movement time, resulting in a less straightforward relationship between movement time and variability in the horizontal direction than in the vertical direction.

As already mentioned, in the blocked condition the movement times for the two orientations of the elongated slow targets were the same. One would therefore expect the same vertical variability. However, the SDv was larger for the tall targets than for the wide ones. This could be caused by subjects not always aiming exactly at the target's center. The SDv is only 0.08 cm larger for tall targets than for short in the random condition and 0.13 cm larger in the blocked condition, whereas the size difference between tall and short targets is 4.16 cm.

In our study the target's speed always affected how quickly subjects hit the targets, whereas there were only modest effects of the target's size and orientation. This suggests that subjects always tried to hit the center of the target, without taking into account that the target's orientation and size determine how precise they need to be, and thus how fast they can or need to move. Our results support Tresilian and his colleagues' conclusion that the required temporal accuracy is not the primary determinant of the variations in movement time. In particular, when subjects have to determine both when and where to hit the target, and different targets are presented in random order, there is no effect at all of differences in temporal accuracy determined by the direction of elongation. If the origin of speed coupling is the difference between temporal accuracy required for fast and slow targets, as we proposed, then our results show that subjects only use speed and size to estimate the "optimum" strategy. This could be because it is too costly (in terms of processing time) to use information about orientation.

Acknowledgements This research was supported by the European Commission (Grant HPRN-CT-2002-00226). We thank two anonymous reviewers for their helpful comments.

References

Brenner E, de Lussanet MHE, Smeets JBJ (2002) Independent control of acceleration and direction of the hand when hitting moving targets. Spat Vis 15:129–140

Brouwer A, Brenner E, Smeets JBJ (2000) Hitting moving objects: the dependency of hand velocity on the speed of the target. Exp Brain Res 133:242–248

Brouwer A, Brenner E, Smeets JBJ (2002) Hitting moving objects: is target velocity used in guiding the hand? Exp Brain Res 143:198–211

Brouwer A, Middelburg T, Smeets JBJ, Brenner E (2003) Hitting moving targets: using the target's direction of motion. Exp Brain Res 152:368–375

Caljouw SR, van der Kamp J, Savelsbergh GJP (2004) Catching optical information for the regulation of timing. Exp Brain Res 155:427–438

Carnahan H, McFadyen BJ (1996) Visuomotor control when reaching toward and grasping moving targets. Acta Psychol 92:17–32

De Lussanet MHE, Smeets JBJ, Brenner E (2001) The effect of expectations on hitting moving targets: influence of the preceding target's speed. Exp Brain Res 137:246–248

Drewing K, Aschersleben G (2003) Reduced timing variability during bimanual coupling: a role for sensory information. Q J Exp Psychol A 56:329–350

Fayt V, Bootsma RJ, Marteniuk RG, Mackenzie CL, Laurent M (1997) The effects of task constraints on the organization of interception movements. J Sport Sci 15:581–586

Fetterman JG, Killeen PR (1990) A componential analysis of pacemaker-counter timing systems. J Exp Psychol Hum Percept Perform 4:766–780

Fitts PM, Peterson JR (1964) Information capacity of discrete motor responses. J Exp Psychol 67:103–112

Harris CM, Wolpert DM (1998) Signal dependent noise determines motor planning. Nature 384:780–784

Ivry RB, Hazeltine RE (1995) Perception and production of temporal intervals across a range of durations: evidence for a common timing mechanism. J Exp Psychol Hum Percept Perform 21:3–18

Landy MS, Goutcher R, Trommershäuser J, Maloney LT, Mamassian P (2004) MEGaVis: perceptual decisions in the face of explicit costs and benefits. VSS Abstract book, T40, 38

Messier J, Kalaska JF (1997) Differential effect of task conditions on errors of direction and extent of reaching movements. Exp Brain Res 115:469–478

Newell KM, Hoshizaki LEF, Carlton MJ, Halbert JA (1979) Movement time and velocity as determinants of movement timing accuracy. J Mot Behav 11:49–58

Savelsbergh GJP, Whiting HTA, Burden AM, Bartlett RM (1992) The role of predictive visual temporal information in the coordination of muscle activity in catching. Exp Brain Res 89:223–228

Schmidt RA (1969) Movement time as a determiner of timing accuracy. J Exp Psychol 79:43–47

Smeets JBJ, Brenner E (1995) Perception and action based on the same visual information: distinction between position and velocity. J Exp Psychol Hum Percept Perform 21:19–31

Tresilian JR, Lonergan A (2002) Intercepting a moving target: effects of temporal precision constraints and movement amplitude. Exp Brain Res 142:193–207

Tresilian JR, Oliver J, Carroll TJ (2003) Temporal precision of interceptive action: differential effects of target size and speed. Exp Brain Res 148:425–438

Tresilian JR, Plooy A, Carroll TJ (2004) Constraints on the spatiotemporal accuracy of interceptive action: effects of target size on hitting a moving target. Exp Brain Res 155:509–526

Trommershäuser J, Maloney LT, Landy MS (2003a) Statistical decision theory and the selection of rapid, goal-directed movements. J Opt Soc Am A 7:1419–1433

Trommershäuser J, Maloney LT, Landy MS (2003b) Statistical decision theory and trade-offs in the control of motor response. Spat Vis 16:255–275

Van Beers RJ, Haggard P, Wolpert DM (2004) The role of execution noise in movement variability. J Neurophysiol 91:1050–1063

Van Donkelaar P, Lee RG, Gellman RS (1992) Control strategies in directing the hand to moving targets. Exp Brain Res 91:151–161

Vindras P, Viviani P (1998) Frames of reference and control parameters in visuomanual pointing. J Exp Psychol Hum Percept Perform 24:569–591