The use of visual information in intercepting moving objects

Het gebruik van visuele informatie in het onderscheppen van bewegende voorwerpen

Proefschrift

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Anne-Marie Brouwer

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Promotor:	Prof. dr. J. G. G. Borst
Overige leden:	Dr. M. A. Frens Prof. dr. H. Collewijn Prof. dr. A. V. van den Berg
Copromotoren:	Dr. E. Brenner Dr. J. B. J. Smeets

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Contents

Chapter 1

General introduction

Intercepting moving objects is complicated

Intercepting moving objects, like catching balls, hitting a ball with a racket in tennis or crushing running insects, can be very demanding for our brain and movement system. Some of the problems the visuo motor system has to face are the same as those in grasping or touching stationary objects. However, the special thing about intercepting *moving* objects is that it will not suffice to determine the object's position and subsequently move to it, but that it is crucial to take into account that the target moves whilst you are planning and moving. This means that you have to move to a *future* position of the target in order to be successful.

To illustrate the complexity of intercepting moving targets, consider the task of crushing a running cockroach. If you want to perform this task, you first have to know several properties of this particular moving target. These properties can be the cockroach's size, its position, its running speed and its running direction. These kinds of visual information about the cockroach have to be picked up and processed. Secondly, information about the position of your own hand or foot is necessary. This can be yielded through vision and proprioception. Thirdly, the visual and proprioceptive information must be combined with (implicit) knowledge or experience in order to determine how to move to which location. Your experience with cockroaches may be that they have very strong shields so your hand or foot has to arrive with great impact to have the effect of crushing. As already mentioned, you should somehow take into account that the cockroach changes its position during your own planning and moving. Fourthly, the movement has to be carried out accurately enough. Furthermore, it should be possible to adjust the movement on the way if the cockroach suddenly decides to run in another direction. It appears that people can do this all within half a second after the cockroach appeared. This is rather amazing and it is poorly understood how this is accomplished.

Scope of this thesis

As indicated above, many different aspects play a role in intercepting moving objects. In this thesis, we concentrate on the use of visual information.

The kinds of visual information that are available and important for intercepting depend strongly on the task. The actions that must be regulated by this information are also very task dependent. Consider the different sources of visual information and the different required actions in catching balls and hitting cockroaches. For a tennis ball moving towards you it is probably important to know how fast it moves in depth. This information could for instance be derived from the ball's changing optical size (Figure 1-1). In order to hit the tennis ball, you may have to walk or run. In the example of the cockroach, where the target's main direction of motion is not necessarily towards you, information about the speed in the cockroach's running direction may be of key importance. Changing optical size is not an optimal cue for acquiring this information, so if information about speed is used it will be derived from another source. In this example, it is not necessary to run but to quickly move your hand or foot. To provide a broad view of the use of visual information in intercepting moving objects, we will consider different tasks. We limit ourselves to short time spans; we consider tasks that are performed within a short period or only consider the first part of the processing and use of visual information.

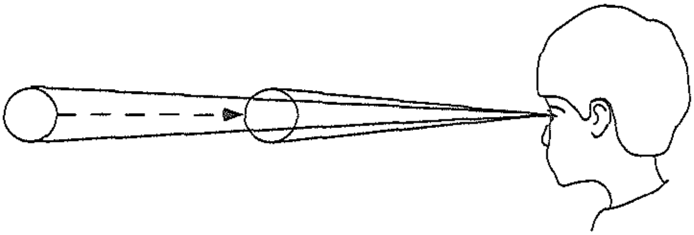

Figure 1-1. The optical size of an object (its visual angle) increases as it approaches the observer.

In thinking about intercepting moving objects, one must take into account that it takes time for stimuli in the world to affect the movement of the intercepting effector. The sudden change in direction of the cockroach you want to crush is only detected after neuronal signals, having traveled from the retina to the brain, are processed. After that, motor commands that take this change in direction into account have to be sent to the muscles. Finally, it also takes time for the motor commands to cause a change in the movement of the hand or foot. The delay of a measurable change of movement direction of the intercepting effector in reaction to a change in the stimulus is in the order of 150 ms (depending on the circumstances, such as the kind of stimulus change; Brenner & Smeets, 1997; Brenner, Smeets & de Lussanet, 1998; McLeod, 1987; Soechting & Lacquaniti; 1983). In many tasks, successful interception cannot be adequately explained if such a delay is simply ignored. Still, some authors do not account for delays in their ideas of how moving targets are intercepted (see chapter 5 on the tau coupling theory for an example).

The possible sources of visual information that we discuss are the target's (changing) position, its speed, its acceleration and the time to contact between the target and the intercepting effector or the time to contact between the target and the position where it has to be intercepted (which are proposed to be directly detectable). Of course, the fact that a certain source of visual information is present does not imply that it is actually used. The information has to be detectable soon enough (one could argue that it is not even information if this criterion is not met) and even if it does, people could be using something else to guide their interceptive movements.

Visual information can be used to regulate different aspects of the intercepting movement. In this thesis we discuss the regulation of the hand's speed and the hand's trajectory in hitting targets that move across a screen. In catching balls, we investigate the catcher's running direction. In intercepting targets with a cursor on a computer monitor, the discussed movement aspect that may be regulated is the time to contact between the intercepting effector and the position where the target has to be intercepted.

In the following section, I will shortly summarize what is said in the literature about the use of the different sources of visual information in the different aspects of the interceptive movement that will be discussed in this thesis, as well as some sources of information and movement aspects that are left aside.

What is known about the use of visual information in intercepting moving objects?

Several authors investigated whether or not certain sources of information are used in (part of) the intercepting action. For some sources of information it is not clear yet whether hitters or catchers use them in particular aspects of the task.

Information about the target's position is obviously used; one does not move towards the floor when hitting a cockroach that is running across the ceiling. As already mentioned, the problem is that the position of a moving target changes while the catcher or hitter is planning and performing the movement, and it changes faster when the target moves fast than when it moves slowly. The catcher or hitter must account somehow for the target's speed. However, it is often difficult to determine whether subjects really used the target's speed or only the target's co-varying position in some aspect of the movement. If someone who hits a cockroach aims further ahead of a fast target than a slow one, this could be caused by the cockroach's speed, but also by the fact that the cockroach's position was further ahead by the time that the movement was planned.

The target's speed has a very consistent effect on the speed of the intercepting effector in many different interception tasks. This effect is that one moves quicker to fast targets than to slow ones (Savelsbergh et al., 1992; Bootsma & van Wieringen, 1990; Fayt et al., 1997; Carnahan & McFadyen, 1996; Wallace et al., 1992; Bairstow, 1987; Smeets & Brenner, 1995; Van Donkelaar, Lee & Gellman, 1992). Moreover, targets that only *appear* to be faster, but do not differ in changing position from apparently slow targets, are hit with quicker movements (Smeets & Brenner, 1995). This shows that it is the target's speed, and not its co-varying position, which is used to regulate the speed of the intercepting effector.

It is less clear whether people take the target's speed into account in guiding the path of the intercepting effector. Bairstow (1987) and Smeets and Brenner (1995) who let subjects hit targets moving across a frontal plane, found that the hand's initial movement direction was not properly adjusted to the target's speed. They suggest that subjects compensate for this by moving faster to fast targets than to slow ones as described in the previous paragraph. However, van Donkelaar et al. (1992) found that the hand's starting direction was adjusted to the target's speed when the reaction time of the subjects was delayed. This could indicate that subjects only need time to adjust the hand's path to the target's speed.

Do people use acceleration in intercepting moving objects? Rosenbaum (1975) presented his subjects accelerating targets in a frontal plane. The targets disappeared behind a mask and the subjects had to indicate when the targets reached a certain point in space. He concluded that acceleration was used. Port et al. (1997), who let their subjects intercept accelerating targets in a frontal plane, reached the opposite conclusion. This discrepancy may be caused by the different kinds of tasks or because the acceleration of the targets used by Port et al. was not high enough to be detected.

Another interception task, for which it is not clear whether acceleration is used, is catching balls that follow parabolic paths. In this case, it is not the acceleration of the target itself that is the matter of debate, but its projection on a virtual vertical plane. If a ball is destined to land ahead of the catcher's position, its projection will decelerate in the vertical direction. Alternatively, if it is destined to land behind the catcher, the ball's projection will accelerate (see Figure 4-5). In order to get at the right position to catch the ball, all that the catcher has to do is run forward if the projection of the ball decelerates and backward if it accelerates, or run in such a way that the speed of the ball's projection is constant (Chapman, 1968). Several authors claim that catchers indeed use this so-called Chapman strategy (Babler & Dannemiller, 1993; Michaels & Oudejans, 1992; McLeod & Dienes, 1996), mainly by showing that the catcher's running behavior is consistent with keeping the velocity of the optic projection constant. Others think it is improbable that this strategy is used because people cannot detect acceleration very well (McBeath, Shaffer & Kaiser, 1995) or because subjects were not good at predicting the relative landing position of balls simulated on a computer monitor (Todd, 1981). However, it has never been directly tested whether people can detect acceleration well enough for using it in this task. Babler and Dannemiller (1993) doubted Todd's conclusion because the acceleration of the stimuli he used may have been too low.

Thus, it remains unclear whether acceleration is used in interception tasks, either in hitting targets moving across a frontal plane, or in determining the running direction and the running speed in catching balls.

Used visual information does not necessarily have to be derived from the current target. Catchers or hitters could expect certain properties of the target based on the properties of previous targets and take these into account in their movement. Van Donkelaar, Lee and Gellman (1992) let subjects intercept targets moving in a frontal plane. They reported that when target velocity did not vary (and the current target velocity could thus be expected from the previous targets), the hand's initial movement direction depended more on the target's speed and the hand paths were straighter than when the target's speed was random. De Lussanet, Smeets and Brenner (2001, 2002), whose subjects performed a similar task, found an effect of the single previous target on the current movement, even when the target's properties were randomly varied. For instance, the initial movement direction and the hitting error depended on the speed of the previous target.

The information and kinds of interceptive actions that are mentioned above will all be discussed in this thesis. Something that will not be discussed is the last phase in catching balls. Here I will shortly discuss possibly relevant visual information during this phase (binocular information) and the final movement in catching balls (closing the hand around the ball).

When a ball is still far away, binocular information will not be very effective, but it could come into play at the end of the catch, when the ball is near the eyes. Servos and Goodale (1998) let subjects catch balls hanging from a rope that were swung to them. They did not find a difference between monocular and binocular viewing conditions. In contrast, Rushton and Wann (1999) who let subjects catch virtual tennis balls, suggest that binocular disparity is used, especially when the simulated ball was small and information from the increasing optical size of the ball was less effective. It seems that the use of binocular information depends on the specific task. In some circumstances subjects may use it, but it may be not be used in easy tasks as when the movement of the target is relatively uniform over the trials (as in Servos & Goodale, 1998) and when another cue provides the necessary information more clearly (as when Rushton and Wann simulated large balls which yields a more effective increasing optical size cue).

Several authors investigated the influence of the target's speed on the grasping of the target. This influence seems to be limited. When subjects have to grasp targets that are moving towards them, the size of the maximum finger aperture is not or hardly affected by target's speed (Chieffi et al., 1992; Carnahan & McFayden, 1996). The grasping time decreases or tends to decrease with increasing speed of the target (Chieffi, et al., 1992; Zaal, Bootsma & van Wieringen, 1998).

A source of information that has often been proposed to be used in timing interceptive actions, is the optic variable tau. Tau indicates the time to contact between the approaching object and the observer. Tau theory arose from the ecological approach. Two theories that will be discussed elaborately in this thesis are also put forward by the ecological approach. These are the Chapman strategy, that I already mentioned, and tau coupling. These theories are two of the few theories that well define (part of) the movement across the complete interception action. As we do not elaborate on the ecological approach in any of the chapters two through five, I will shortly discuss it here (for a more complete description, see Gibson, 1979) and explain tau and tau coupling within its framework.

The ecological approach

Ecological psychology is a reaction to the constructivist (or Helmholtzian) tradition. This tradition is characterized by performing controlled experiments in impoverished surroundings (e.g. in a dark room with the subject's head fixed). Constructivists assume that observers construct a representation of the external world, using (unconscious) knowledge or memory besides sensory inputs. In contrast, ecologists argue that all necessary information about the visual environment is present in the optic array (the light reflecting from all objects in the world). Representations and unconscious computations do not exist: they are not necessary, as the external world is perceived directly instead of being constructed from sensations and knowledge. According to ecologists, constructivists were led to assume that the world cannot be known through visual input alone, because they used artificial experimental stimuli. The natural environment does provide sufficient information. Direct perception is possible through so-called invariants, which are optical variables that specify (the value of) a certain property of something in the external environment. (See Gordon, 1989 for an elaborate comparison between the constructivistic and ecological approach.)

Probably the most famous example of a (proposed) invariant is tau. In the original paper (1976), Lee argued that the time to contact between a driver and an obstacle was specified by tau, defined by the inverse of the relative rate of expansion of the obstacle's optical image. Tau provides a clear illustration of the idea of direct perception. By using tau, an observer does not have to compute the time to contact from the distance between the car and the obstacle and the speed of the car. There are many papers proposing that tau is used in intercepting moving objects. Savelsbergh et al. (1992) and Lee et al. (1983) suggest that ball catchers or ball punchers initiate their interceptive movement when tau, in this case the inverse of the relative rate of expansion of the ball's optical image, reaches a certain value. Wallace et al. (1992) let subjects catch an object that was not on an intersection trajectory. They suggest that though in this case subjects do not simply initiate their movements at a critical tau value, subjects do establish a coupling between the movement time and the value of tau at the time of movement initiation. Something similar is suggested by Bootsma and van Wieringen (1990) who studied timing in table tennis. Ball punchers in a study by Michaels, Zeinstra and Oudejans (2001) did not initiate their action at a specific tau value as well, but Michaels et al. concluded that tau was used in rate of change of elbow angle. Recently, Lee (1998) elaborated the tau theory to a theory called tau coupling. For this theory, tau is defined as the time to closure of a decreasing gap. It is proposed that in order to perform goal-directed behavior, the tau of one decreasing gap is kept in constant ratio to the tau of another decreasing gap so that both taus reach zero simultaneously. For example, when a subject has to intercept a target at a specified goal zone, she or he could intercept the target by keeping the tau of the gap between target and goal zone in constant ratio to the tau of the gap between the interception effector and the goal zone. This proposed strategy is in line with the ecological approach, as it describes the complete interception without representations of the target and without computing its future positions.

Another example of an invariant and a typically ecological interception strategy is already mentioned in this introduction. The invariant is the acceleration of a ball's projection, which specifies whether a ball will land ahead or behind a catcher. The strategy to get to the right position to catch the ball is running in such a way that the speed of the ball's projection is constant. Like tau coupling, this strategy explains (part of the) interception without predictions or computations of the catcher. An example of a constructivist proposed strategy would be that before starting to run, the catcher computes the time and place of the ball's landing by using distance and speed information, combined with the knowledge of gravity and with the experience that such balls will follow an (approximately) parabolic trajectory.

My view on the ecological approach

In looking for invariants, the ecological approach promoted a thorough exploration of the visual information that is present in the external world. Also, ecologists clarified the danger of artificial laboratory experiments. They reminded scientists of the fact that perception is not about detecting tiny speed differences between two moving dots in a dark room, but about surviving in the real world. However, it seems that the ecological approach underestimates the complexity of perception and action. It would be nice if there really were invariants for all the information one needs and if one could explain all actions like choosing the running direction in catching balls by something (relatively) simple like detecting the difference between acceleration and deceleration. Unfortunately, it proved to be very difficult, firstly, to find invariants, and secondly, to show that they are actually used. Although tau is perhaps considered to be the clearest example of the success of the ecological approach, tau does not exactly specify time to contact if the target is not moving at a constant speed and if the point of interception is not at the eye. In some circumstances, the difference between tau and the real time to contact seems to be intolerably large (Tresilian, 1991). Further, despite numerous studies on the use of tau, it has never been shown convincingly that tau is used in timing actions or in determining time to contact (for an overview, see Wann, 1996; Tresilian, 1999). Other ways of estimating time to contact have been proposed (Moliner & Bonnet, submitted; Kerzel, Hecht & Kim, 1999).

The ecological notion that all that is necessary is the information in the optic array seems to be incorrect. The behavior of for example, someone playing table tennis, can be positively affected by some advice from the trainer. How could this be explained without assuming that knowledge is combined with visual information?

A final drawback of the ecological approach is that many ecological terms are not clearly defined. What exactly is 'direct' perception? Ecologists argue against constructing perception from different sensations, but how *does* it happen? According to ecologists, information 'resonates' with the nervous system or is 'extracted' by it (Gibson 1966, p 5 and Gibson 1979, p 246). This is rather unclear. If it turns out that there is a neuron that responds to tau (actually, this has been claimed by Sun and Frost, 1998), and it appears that it gets its input from neurons responding to visual angle and the rate of expansion, should one conclude that the tau neuron directly perceives tau or that it computes tau from the sensations of visual angle and the rate of expansion? Indeed, terms like 'representation', 'computing' and 'knowledge' may sound overdone when describing something that you can do so quickly and automatically, like catching balls. But principally objecting to approaches in which these terms are used, may be unjust.

In summary, we do not approach our questions of research from an ecological point of view (as may have been noticed when reading the first part of the introduction). However, I do appreciate some of the ideas that have been put forward by ecologists.

Short outline of chapters 2 through 5

It has consistently been found that fast targets are intercepted with faster movements than slow targets. In *chapter 2* we let subjects hit virtual spiders to test the hypothesis that information about the spider's speed is used in controlling the speed of the hand, in order to compensate for the inability to account for the spider's speed in the hand's trajectory. We found that this hypothesis is incorrect. Another possible reason for coupling the speed of the hand to the speed of the target is discussed. As adjusting the hand's speed is apparently not the only strategy to deal with targets moving at different speeds, people probably do take the target's speed into account in the hand's path.

In *chapter 3* we asked ourselves whether it is really the target's speed or the co-varying target's position that is used in planning the hand's trajectory. We investigated this by letting subjects hit spiders that became invisible. We concluded that people use the target's position. If the target's speed is not used in guiding the hand's trajectory, it seems improbable that the target's acceleration can be used in intercepting moving targets. However, from the experiments described in chapter 3 it appeared that there was an effect of speed on the hand's trajectory, though we think this came about via a speed-related misperception of the target's position. Perhaps, subjects can also account for acceleration using such a roundabout way. Several authors suggest that in catching fly balls, the distinction between acceleration and deceleration of the projection of a ball is used to determine the running direction.

We thus examined in *chapter 4* whether information about the target's acceleration can be used in intercepting. We measured how much change in speed is needed to detect acceleration. This appeared to be too much to be of possible use in tasks like hitting spiders. By examining ball-catching data of Oudejans, Michaels and Bakker (1997) we showed that people already start running before they could have distinguished between acceleration and deceleration. Thus, information about acceleration is also not used in catching balls. We propose an alternative source of information for determining the correct running direction.

In *chapter 5* we discuss a recent theory called tau coupling. It proposes that goal directed tasks are controlled by keeping the time to closure of one decreasing gap in a constant ratio to the time to closure of another decreasing gap. Amongst other things, this theory has been used to explain visuo motor control in intercepting moving objects. Besides mentioning some theoretical problems with tau coupling, we used simulated interception data to show that the method that is used to provide evidence for tau coupling is not valid.

Chapter 2

The dependency of hand velocity on the speed of the target

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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 only necessary when subjects are unable to correctly predict the next target velocity, and only if they have to be accurate. We here show that decreasing the uncertainty about the up-coming 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.

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 has been used to study interception of moving objects. Subjects 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 Mc Fadyen, 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, 1995a) or their hand (Van Donkelaar, Lee and Gellman, 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, 1995a). 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 (1995a) 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 which 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.

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

(1995a) 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: in this case 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 in 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.

Methods

Materials

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 Figure 2-1.

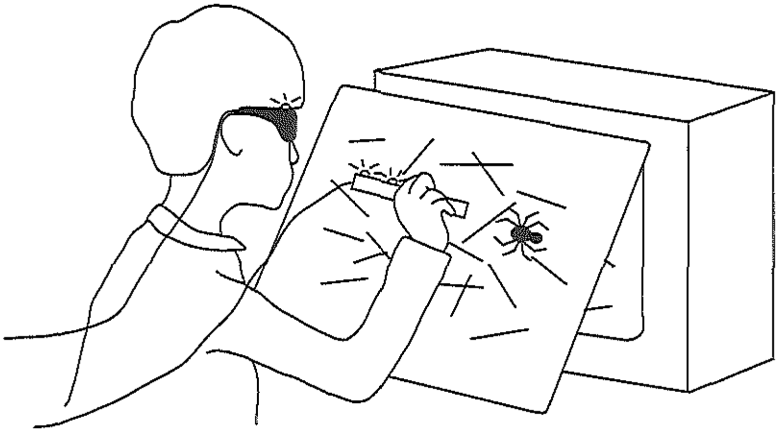

Figure 2-1. A schematic view of the experimental setup. The subject sits in front of the monitor on which the stimuli are presented. Shutter glasses make the stimuli appear on a protective screen. IRED's are attached to the hitting rod and the glasses so that the position of the head and the rod can be determined.

Subjects used a 22-cm long Perspex rod to hit simulated spiders which were running over 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 to appear 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, 12 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 will give rise to an error of 0.66 cm when the spider moves 6 cm/s slower or faster than the average speed of 12 cm/s. This is the systematical 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 will make an error of at most (5.5 cm / 2) + 0.66 cm = 3.41 cm. Because the error they are allowed to make with the large tipped rod is 3.6 cm, they do 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 about 1.8 cm. The spider always started 8 cm to the left of the rod, as we learned from earlier experiments that this will result in hand paths which 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 were 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. 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 was 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 Figure 2-2. Data were collected in three conditions, which were presented during three sessions, with intervals of 3 hours 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, 12 and 18 cm/sec) 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, 12 and 18 cm/sec, 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.

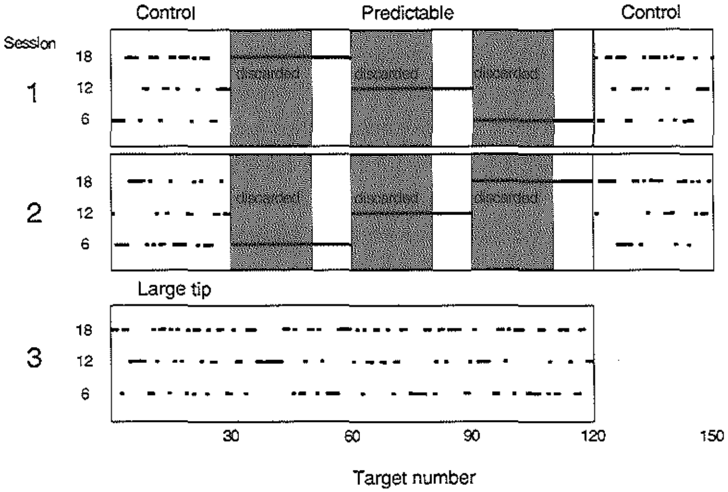

Figure 2-2. An overview of the design. There were three experimental sessions, with spiders running at three different velocities (6, 12 and 18 cm/s). In each of the first two sessions subjects used the normal hitting-rod to hit the spiders. Each of these sessions consisted of parts in which the target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

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 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 not only determined separately 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 Figure 2-3A. As already found by others (e.g., Savelsbergh et al., 1992; Van Donkelaar et al., 1992; Smeets and Brenner, 1995a), subjects react quicker when the target moves faster (for an explanation see Smeets and Brenner, 1994). Moreover, the overall mean reaction time is significantly shorter in the large tip condition than in the control ($t_{29}=-8.18$, $p<0.01$).

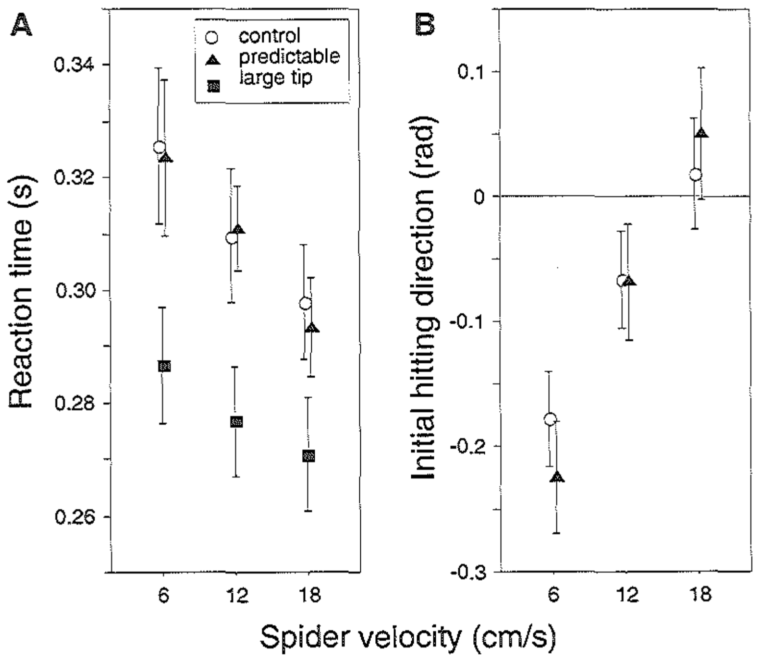

Figure 2-3. Reaction time and initial hitting direction. Error bars represent the standard error between subjects. **A** Reaction time per spider velocity and per condition. Reaction time decreases with target velocity. **B** Initial hitting direction per spider velocity in the control and the predictable 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 to the other conditions due to differences in reaction time.

Initial hitting direction

As is shown in Figure 2-3B, subjects take more consideration of the target's velocity when initiating their movements 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 Figure 2-3A shows, this cannot be attributed to differences in reaction time.

Maximal hand velocity and speed coupling

In Figure 2-4A 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 Figure 2-4B 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 0 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.

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 Figure 2-5, the strength of speed coupling correlates negatively 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 Figures 2-3B and 2-4A, 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 Figure 2-4) 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.

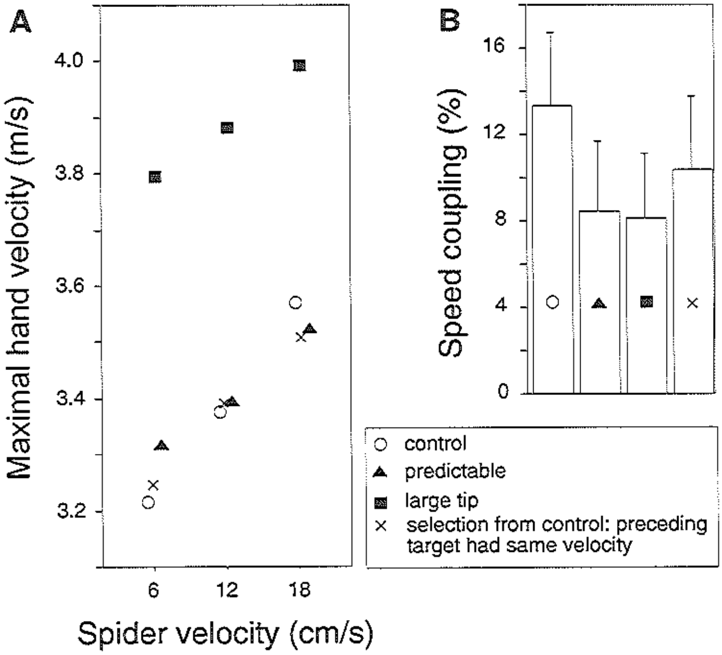

Figure 2-4. Maximal hand velocity and speed coupling. The crosses represent selected data from the control condition: they indicate the mean maximal velocity toward spiders that were preceded by a spider moving at the same velocity. **A** Maximal hand velocity for each spider velocity and each condition. 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.

Systematic error

Figure 2-6A shows the mean lateral hit error per spider velocity and per condition. The mean hit error is always larger than 0, 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 Figure 2-6B. 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 and 99% in the large tip condition.

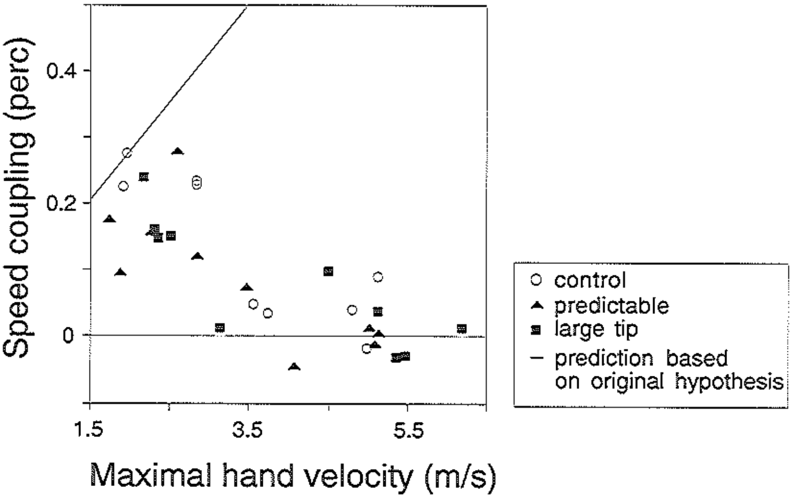

Figure 2-5. Negative correlation between strength of speed coupling and maximal hand velocity ($R^2=0.7$). Every subject is represented by one point for each condition, i.e., 3 points per subject. The oblique line depicts the relation between the maximal hand velocity and strength of speed coupling predicted on the basis of our original hypothesis (see also Brenner and Smeets, 1996 and discussion).

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.

Though 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.

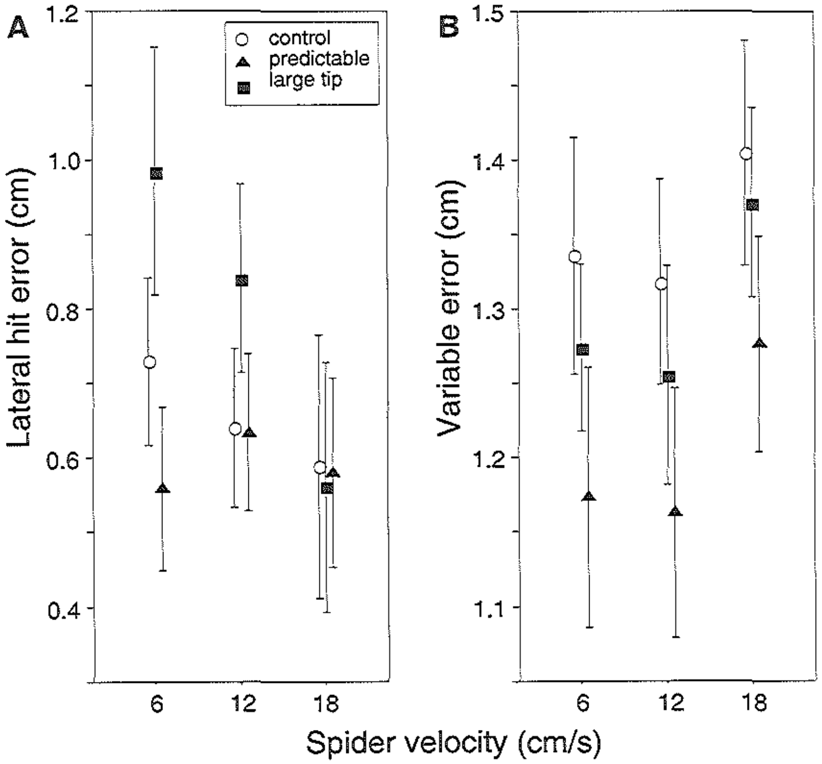

Figure 2-6. Hit error per spider velocity in the three conditions. Error bars represent standard errors between subjects. **A** Systematical error. Only the lateral direction of the errors is considered. The center of the spider is located at 0; positive values indicate a bias toward hitting in front 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.

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 thirty 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 (Figure 2-6) 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 (Figure 2-3B).

Additional, conclusive evidence that the hypothesis cannot be correct is presented in Figure 2-5. 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 in 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 Figure 2-5. 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 systematical 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 get 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, 12 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 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 towards 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: e.g. 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 systematical 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 Figure 2-6A), 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.

Chapter 3

Is target speed used in guiding the hand's path?

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Abstract

We investigated what information subjects use when trying to hit moving targets. In particular, whether only visual information about the target's position is used to guide the hand to the place of interception or also information about its speed. Subjects hit targets that moved at different constant speeds and disappeared from view after varying amounts of time. This prevented the subjects from updating position information during the time that the target was invisible. Subjects hit further ahead of the disappearing point when the target moved faster, but not as much as they should have on the basis of the target's speed. This could be because more time is needed to perceive and use the correct speed than was available before the target disappeared. It could also be due to a speed-related misperception of the target's final position. The results of a second experiment were more consistent with the latter hypothesis. In a third experiment we moved the background to manipulate the perceived speed. This did not affect the hitting positions. We conclude that subjects respond only to the changing target position. Target speed influences the direction in which the hand moves indirectly, possibly via a speed-related misperception of position.

Introduction

In order to catch a ball, you have to take into account that the ball moves during your own movement. This means that you have to guide your hand to a future location of the ball and to arrive there in time. It is not known what visual information is used, and in what way, to guide the hand to the correct place at the correct time.

A large number of previous studies and theories about the interception of moving objects emphasized the temporal aspect of the task. Examples are the studies about the optic variable tau (the ratio of image size to its expansion velocity) which (approximately) specifies time to contact between an approaching object and the potential catcher or hitter (Lee et al. 1983; Savelsbergh et al. 1991). In these studies it is proposed that subjects initiate their action when tau reaches a certain value. Michaels et al. (2001), Tresilian (1999) and van der Kamp et al. (1997) showed that it is not that simple, but they too concentrated on the timing. Something that certainly contributed to the emphasis on the temporal aspect of interception is the use of tasks in which subjects had to intercept targets in a more or less predestined area (Carnahan and McFayden 1996; Mason and Carnahan 1999; Port et al. 1997; Tresilian 1994). This makes temporal variables such as reaction time and movement time critical.

Other investigators did not specifically look at either temporal or spatial aspects, but viewed interception as a continuous coupling of action to the changing visual information about the target (Montagne et al. 1999; Peper et al. 1994; Smeets and Brenner 1995a; Zaal et al. 1999). The disadvantage of models that are generated by this approach is that they are often very complex and therefore difficult to test. An exception is the proposed strategy of actively canceling the acceleration of the optical image of the ball in the vertical direction (Babler and Dannemiller 1993; Michaels and Oudejans 1992). Subjects reach the point of interception (with a ball that is approaching via a parabolic path) by running backwards if the image accelerates and forward if it decelerates. However, this model probably cannot account for human performance (Brouwer et al. 2001; McBeath et al. 1995; Todd 1981) and only applies to a very specific task. It cannot be used to explain performance when intercepting targets that move perpendicularly to the movement of the hand.

As the spatial aspect of interception has received very little attention, we chose to investigate this in the present study. The timing was more or less fixed by instructing subjects to be as fast as possible. We examined where they intercept the target. We are particularly interested in whether, and if so how, subjects use the target's speed in guiding the hand to the place of interception.

An alternative to using the target's speed is to assume a certain target speed, and to continuously update the position toward which one is aiming on the basis of the target's constantly changing position (Smeets and Brenner 1995a). According to this view, the only visual information about the current target that is used is its position. The assumed speed may be a (weighted) average of the speeds of previous targets (de Lussanet et al. 2001). We will refer to this as a default speed.

In the literature there are some indications that subjects use position and a default speed instead of the actual target speed to 'intercept' moving objects. One of these comes from a study about saccadic eye movements in response to step-ramp stimuli (Heywood and Churcher 1981). Subjects made a saccade towards a dot that jumped to the right and immediately moved rightward at a randomly chosen speed. To reach the target, subjects had to take the target's motion into account when planning the saccade. The results suggested that target speed was not used in doing this. Instead, in order to determine where to move with their eyes, subjects appeared to take the target position 100 ms before the saccade and to make a saccade to a position that was a fixed distance to the right of this.

There are also studies about manual interception in which the authors conclude that target speed is hardly used to guide the hand. Bairstow (1987) asked subjects to intercept moving targets that were presented on a monitor. He found that the starting direction of the hand hardly depended on target speed. In a similar task, Brenner and Smeets (1996) also found that subjects started to move as if they expected all targets to move at the same speed. However, van Donkelaar et al. (1992) suggest that if the reaction is delayed, the direction in which the hand starts to move does depend on the target's speed. Therefore, the starting direction may not be a suitable variable to investigate whether subjects use target speed in guiding their hand, since speed information may only manifest itself later in the movement. This might be because it takes relatively long to perceive the target's speed and transform this information into control of the muscles (Brenner et al. 1998).

It may seem a bit strange to distinguish between speed and changing position. Physically, speed is nothing more than the change of position over time. However, physiologically, the perception of position and speed seem to be separated. This can be demonstrated with the motion aftereffect (reviewed by Anstis et al. 1998). If you look at something stationary after having looked at a moving stimulus for some time, the static object appears to move. However, it does not appear to change its position accordingly. A similar dissociation is found when the background is moved. This changes the perceived speed but has no influence on the perceived position (Smeets and Brenner 1995a).

In general, it is very difficult to disentangle the use of speed from that of position. In interception tasks, it is not enough to look at the direction in which the hand moves, because the changing position of a stimulus varies with its speed. If a subject moves his or her hand to a position further ahead of a fast target than of a slow one, this may be caused by the difference in speed, but it may as well be an effect of the difference in position. To investigate whether subjects use the actual speed of the present target to guide the hand to the interception point, or only use the target's position and a default target speed, we let subjects hit virtual spiders that moved at different speeds from the left to the right. After some time, the spiders disappeared from view. This prevents subjects from using information about the changing position of the target during the time it is invisible (Rosenbaum 1975). The position of the hit therefore reflects the speed subjects use to guide the hand to the target's position at the time of interception. We are interested in whether this is the actual or a default speed.

Experiment 1

We constructed two subsets of conditions. One subset tested the predictions of the hypothesis that, besides the target's position, the actual speed is used. The other tested the predictions of the hypothesis that only the position and a default speed are used. These two hypotheses are hereafter simply called hypothesis of actual and default speed, respectively. The first subset consisted of conditions in which spiders started at the same positions and moved at equal speeds but were visible for different times. If the actual speed of the target is used in guiding the hand to the interception point, the subjects should hit the same position in space, irrespective of the amount of time that the spiders were visible. The second subset of conditions was designed to examine the hypothesis that a default speed was used. In this subset, spiders that differed in speed disappeared at the same position after having been visible for the same amount of time. If subjects use a default target speed to guide the hand to the interception point, they should, on average, hit the same distance ahead of the point at which the spiders disappeared, irrespective of the speed at which the spiders ran before they disappeared. By testing the hypothesis in this way, we did not have to assume a particular value for the default speed. To be able to evaluate the hypotheses quantitatively, we transformed them into models that predict where the subjects will try to hit the targets. For this analysis we did have to specify the default speed; we assumed that it was the average target speed.

Methods

Materials

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 Figure 3-1.

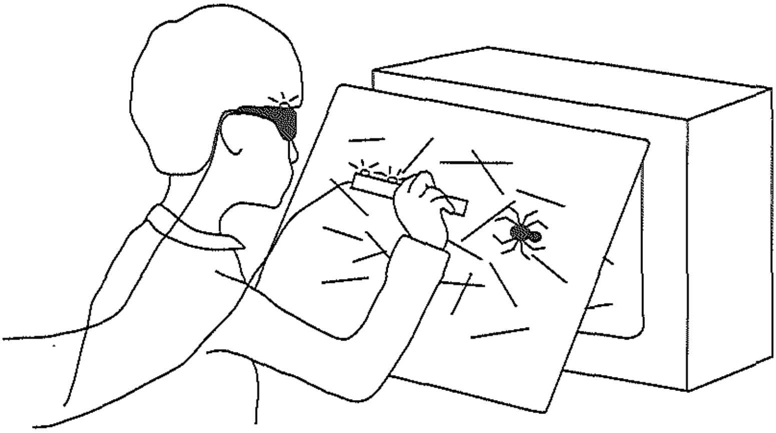

Figure 3-1. A schematic view of the experimental setup. The subject sits in front of the monitor on which the stimuli are presented. Shutter spectacles make the stimuli appear on a protective screen. IREDs attached to the spectacles and the hitting rod allow the position of the head and the rod to be determined.

Subjects used a 22-cm long Perspex rod to hit simulated spiders that were running to the right over a background. A background was used to make the task more naturalistic and to facilitate the perception of the spider's motion and distance. 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 to appear to be situated on a transparent Macrolon screen. The screen was placed in front of the monitor to protect the monitor 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. The rod was typically held in such a way that the tip was about 1 cm from the fingertips. The spider was yellow and had 1.5-cm legs, consisting of three segments. The legs moved as a real spider's would. The spider's body consisted of three segments with a total length of 0.85 cm. Including the legs its length was about 1.8 cm. The virtual height of the spider's body was 1.5 mm. The spider moved across a background of 4-cm red lines. The lines were placed at random 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. Since subjects were free to move their head, the magnitude of the stimulus in terms of visual angles varied during the trials and between subjects. In general, 1 cm on the screen corresponds to about 1 degree of visual angle.

Three infrared markers (IREDs) on the hitting screen were used to calibrate the setup before the experiment began. Three more 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 were also used on-line during the experiment.

Information was needed about when and where the screen was hit, so that feedback could be given. As soon as the screen was hit, the spider appeared again. If it was a successful hit (if the center of the rod came within 1.8 cm of the center of the spider) the spider looked crushed, whereas if the subject missed the spider, the latter ran away from the rod in the direction opposite to the error. Note that this feedback was consistent with the use of the actual speed.

Information about the position of the rod was also necessary to help the subjects position the rod at the beginning of a trial. The rod had to be within 5 cm from a point 40 cm horizontally away from the center of the protective screen. Directions were given on the screen about where to hold the rod (e.g., "further to the left"), and a green line that pointed out of the screen indicated the direction in which the rod had to be held. The next trial did not begin until the hand was in the required position. Otherwise, the subject was allowed to sit any way he or she wanted.

Information about the position and orientation of the spectacles was needed to determine the position of the subject's eyes in space (note that the orientation of the eyes with respect to the head was not measured). Eye positions were necessary to calculate appropriate images for the two eyes.

The delay in adjusting the stimuli to the subjects' movements was 21±3 ms.

Design

The spiders ran at 6, 12 or 18 cm/s. The time for which the spiders were visible (T_{vis}) was 150, 250 or 350 ms. These times were chosen to be sure that the spider almost always disappeared before the subject hit the screen, but still to present the spiders long enough for subjects to judge their speeds.

As already mentioned, there were two (overlapping) subsets of conditions, each designed for examining one of the two hypotheses (see Figure 3-2 for an overview). In the subset for examining the hypothesis of actual speed, there was one starting point for each spider speed. Each T_{vis} was used for each spider speed (v). This resulted in 3 (v) * 3 (T_{vis}) = 9 conditions. In the subset for examining the hypothesis of default speed, there was one position at which the spiders disappeared for each T_{vis}. Spiders running at each speed were visible for each T_{vis}. The number of conditions in the second subset was therefore 3 (T_{vis}) * 3 (v) = 9. The total number of conditions in the experiment could be restricted to 13, because five of the conditions belonged to both subsets. Each condition was repeated 15 times, which resulted in 195 trials per subject. The order of the trials was completely random.

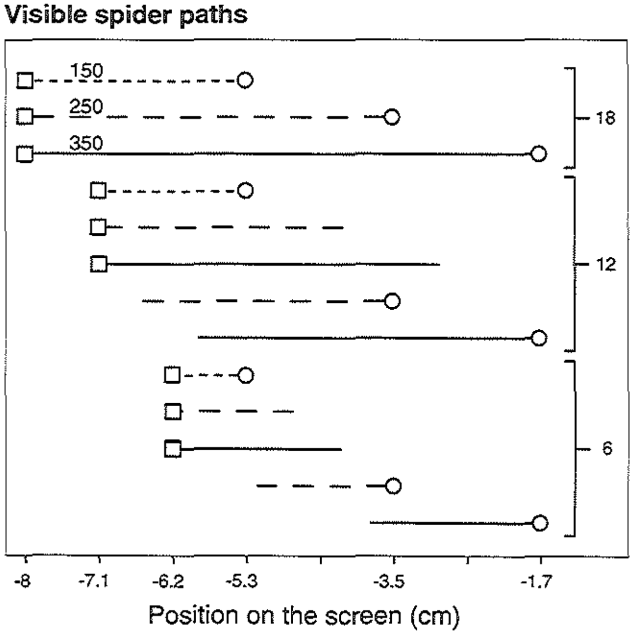

Figure 3-2. An overview of the design of Experiment 1. The lines represent the paths of the spiders during the time that they are visible. Positions are relative to the projection on the screen of the hand's starting position. The time that the spiders are visible (T_{vis}: 150, 250 or 350 ms) is coded by the type of line, the spider speed (in cm/s) is indicated on the right of the paths. Conditions belonging to the subset of spiders that examines the use of actual speed are marked by a square at the starting point. Conditions belonging to the subset that examines the use of a default speed are marked by a circle at the disappearing point. Five conditions belong to both subsets.

Subjects and instruction

Ten volunteers, mostly from our department, participated in the experiment. They gave informed consent before participating. They were all right-handed and hit with their right hand. The subjects were instructed to hit the spiders as quickly as possible with the rod. We told them that the spiders would become invisible, but that they kept on running at the same speed and in the same direction, so it would still be possible to hit them. The feedback was also explained. Subjects could take a break whenever they liked by not returning their hand to the starting position.

Analysis and models

From a total of 1950 trials, 43 were excluded from analysis for technical reasons (primarily because markers were hidden from view because the subject turned the rod). Another 11 trials were not analyzed because subjects arrived at the screen before the spider had disappeared. Seven more trials were discarded because the subject did not react within 600 ms or needed more than 1000 ms to move the hand from the starting position to the screen.

A number of measures were defined (Figure 3-3). The spider position is the (invisible) spider's lateral position at the time of the hit. The hitting position refers to the lateral position of the tip of the rod when it hits the screen. Both are measured relative to the starting point of the spider. If a subject hits the center of the spider, spider position and hitting position have the same value. The hitting error is the horizontal difference between the hitting position and the spider position. If the subject hits to the right of the spider's center, the hitting error has a positive value. If the subject hits to the left, its value is negative. The variable error is the standard deviation of the hitting error. It is determined separately for each T_{vis}, spider speed and subject. The invisible displacement is the distance between the disappearing point and the spider position. The used invisible displacement is the distance between the disappearing point and the hitting position. This distance reflects the speed that the subject has used to guide his or her hand. According to one hypothesis this will be a default speed. According to the other it will be the actual speed.

We also measured reaction time (*RT*) and movement time (*MT*). Reaction time is defined as the time between target onset and the moment that the speed of the hand exceeds 0.1 m/s. Movement time is the time between movement initiation and arrival on the screen.

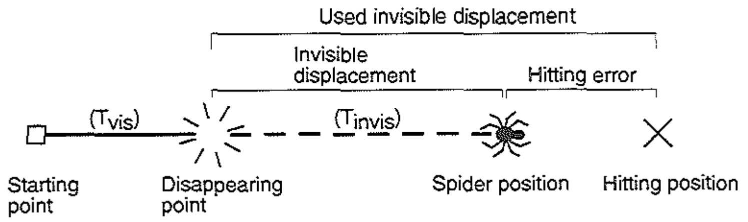

Figure 3-3. Schematic overview of several used variables. T_{invis} is the time that the spider is invisible.

All statistical analyses concern both hits and misses. Differences between conditions were evaluated with repeated measures analyses of variance with target speed and T_{vis} as factors. The input for the analyses were averages for each subject, target speed and T_{vis}. We took $p<0.05$ as the level of significance.

We also transformed the two hypotheses into models that quantitatively predict the invisible displacements. The models are based on the assumption that the positions at which subjects hit the screen are where they want to arrive, and that systematic timing errors, which would introduce systematic spatial errors, are not made. For each trial and each model, we computed the predicted invisible displacement (*PID*). For the hypothesis that actual target speed (v) is used, the predicted invisible displacement was computed as

$$PID = T_{invis} * v, \qquad (1)$$

where T_{invis} represents the time that the spider is invisible, i.e., the time between disappearance of the spider and the arrival of the hand on the screen. For the hypothesis that a default speed is used to guide the hand instead of the actual speed, we defined the default speed v_d as the average speed of all targets (i.e., 11 cm/s)[1]. The predicted invisible displacement was computed as

$$PID = T_{invis} * v_d \qquad (2)$$

To evaluate the models, we determined the average used invisible displacement and compared it with the average predicted invisible displacement for each subject and each condition. To see whether the mean deviation of one model from the data was significantly different from that of the other, we performed a paired t-test on the average deviations (paired by subject and condition).

Results

General characteristics

The reaction time (Figure 3-4A) does not depend on the time that the spider is visible ($F_{(2,18)}<1.0$, $p=0.92$). As found in previous studies (e.g., Savelsbergh et al. 1992; Smeets and Brenner 1994), it decreases with increasing target speed ($F_{(2,18)}=6.33$, $p<0.01$). The movement time (Figure 3-4B) decreases with increasing T_{vis} ($F_{(2,18)}=3.91$, $p=0.04$) but the difference in average movement time between the longest and shortest T_{vis} is only 3 ms. The movement time is shorter when the spider moves faster ($F_{(2,18)}=34.67$, $p<0.01$). The variable error (Figure 3-4C) decreases with increasing T_{vis} ($F_{(2,18)}=9.45$, $p<0.01$) and is independent of spider speed ($F_{(2,18)}=1.62$, $p=0.22$).

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[1] We examined whether taking the speed of the previous spider instead of the average speed as the default speed improved the predictions of the default speed model. This was not the case.

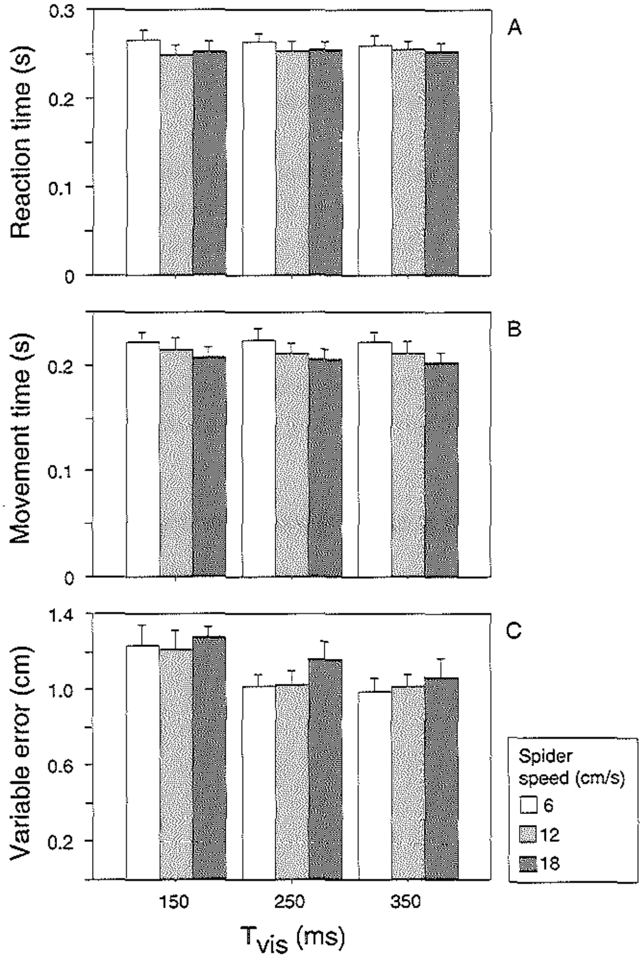

Figure 3-4. Reaction time, movement time and variable error per T_{vis} and per spider speed. Error bars represent the standard error between subjects. **A** Reaction time is independent of T_{vis} and decreases significantly with target speed. **B** Movement time decreases with T_{vis} and target speed. **C** Variable error becomes smaller when the spider is visible longer. Target speed does not significantly influence the variable error.

Subjects could do the task remarkably well. The spiders were hit successfully in 79% of the trials. The number of hits depended on how long the spiders were visible; 70% of the spiders with a T_{vis} of 150 ms were hit, which increased to 79% and 84% when the spiders were visible for 250 ms and 350 ms respectively. Fast spiders were more difficult to hit (73% successful hits) than slow and intermediate spiders (both 81%).

Our main interest is how the position of the hit depended on the experimental conditions. This will be discussed below.

Subset of conditions examining the use of actual speed

If subjects had used the actual speed, they would have hit spiders running at the same speed at the same position, irrespective of the time they were visible. In contrast, Figure 3-5 shows that the hitting position was influenced by the time the spider was visible ($F_{(2,18)}=11.89$, $p<0.01$). Fast and intermediate spiders were hit further behind their centers when they were visible for 150 ms than when they were visible longer (significant interaction of T_{vis} and target speed on hitting position and on hitting error: $F_{(4,36)}=13.26$ and $F_{(4,36)}=17.57$ respectively, both p-values <0.01). The faster the spider, the more the hitting error (the difference between spider position and hitting position) depended on T_{vis}.

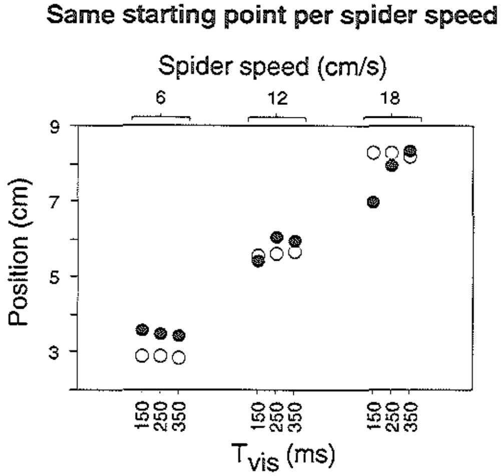

Figure 3-5. Mean spider positions (open circles) and hitting positions (solid circles) for the subset of conditions that tests the use of actual speed. Positions are measured relative to the start of the spider's movement. The larger the value for position, the more to the right the spider had moved at the time of the hit (spider position), or the more to the right subjects hit (hitting position). In contrast to the predictions of the hypothesis of actual speed, hitting position depends on the time the spider was visible.

Subset of conditions examining the use of a default speed

If subjects had used the position and a default speed, they would have hit the same distance in front of the disappearing point for each T_{vis}, irrespective of the spider speed. This is clearly not the case (Figure 3-6): they hit further ahead of the disappearing point for fast spiders than for slow ones (significant effect of spider speed on used invisible displacement: $F_{(2,18)}=1027.40$, $p<0.01$). Comparing the open and solid symbols shows that the hitting error was less dependent on spider speed when the spiders were visible longer (significant interaction of target speed and T_{vis} on hitting error; $F_{(4,36)}=22.73$, $p<0.01$).

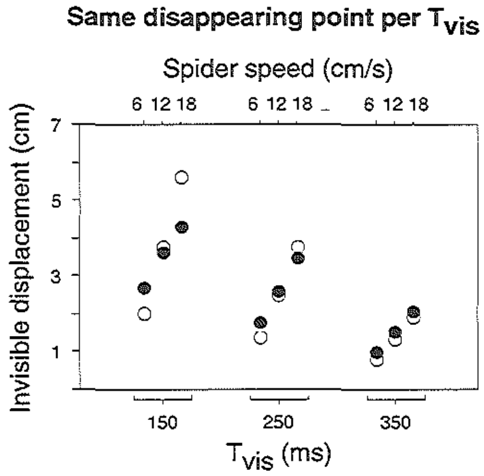

Figure 3-6. Used invisible displacements (solid circles) and actual invisible displacements (open circles) from responses to the subset of conditions that tests the use of a default speed. In contrast to the predictions of the hypothesis of default speed, subjects hit further ahead of the disappearing point for fast spiders than for slow ones. Hitting error becomes less dependent on spider speed with increasing T_{vis}.

Models

We compared the used invisible displacements with the invisible displacements predicted by the two models (Figure 3-7). The mean deviation of the used invisible displacements from the predicted invisible displacements is 0.40 cm for the actual speed model and 0.49 cm for the default speed model. The mean deviations were on the border of being significantly different ($t_{129}=1.95$, $p= 0.05$).

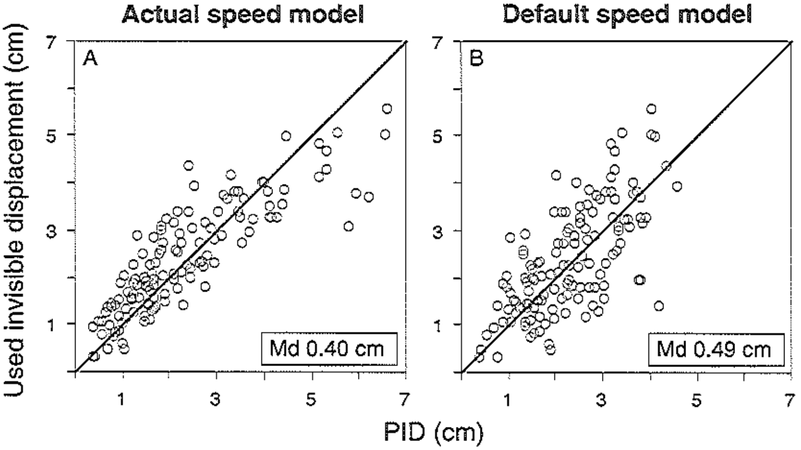

Figure 3-7. The used invisible displacement (ordinates) averaged for each subject and each condition plotted against the invisible displacement predicted by **A** the model that uses the actual spider speed and **B** the model that uses a default speed (abscissas). The straight line is the unity line. The mean deviation (Md) of the points from the unity line is given in the lower right corner of each figure .

Discussion

If actual target speed had been used correctly to guide the hand to the interception point, spiders starting at the same position and running at the same speed would have been hit at equal positions on the screen, irrespective of the time they were visible. This seems to be true for the slow spiders, but hitting positions are not equal for different values of T_{vis} for the spiders running at 12 and 18 cm/s (Figure 3-5). This result suggests that a default speed of about 6 cm/s was used. However, if a default speed had been used to predict the interception point, the used invisible displacements would not have differed between spiders with equal disappearing points and an equal T_{vis} but different velocities. Figure 3-6 clearly shows that the used invisible displacements did differ. Thus, both hypotheses can be rejected on qualitative arguments. Analysing the results quantitatively with the models failed to distinguish between the hypotheses of actual and default speed (Figure 3-7).

The results presented in Figure 3-6 suggest that actual and default speed are both used in hitting moving spiders, but both only partly. If subjects only used the actual speed, they would have hit the spiders correctly (maybe with a small bias). If subjects used a default speed, they would have hit the same distance ahead of spiders that were visible for the same time. Figure 3-6 shows that the result is something in between, though the longer the spiders are visible, the more the actual speed seems to be used.

In the following, we will examine two hypotheses which incorporate the notion that default speed and actual speed both play a role in guiding the hand to the interception point. They also both predict that the influence of actual target speed increases with T_{vis}. The first hypothesis is called the extrapolation hypothesis, the second is the hypothesis of progressive use of speed. Like the hypothesis of default speed, the extrapolation hypothesis assumes that subjects guide their hand on the basis of target position and not speed. The effect of target speed arises from a speed-related misperception of target position. The hypothesis of progressive use of speed refines the hypothesis of the actual speed. It assumes that speed itself is used, but considers that time is needed to perceive and use speed information.

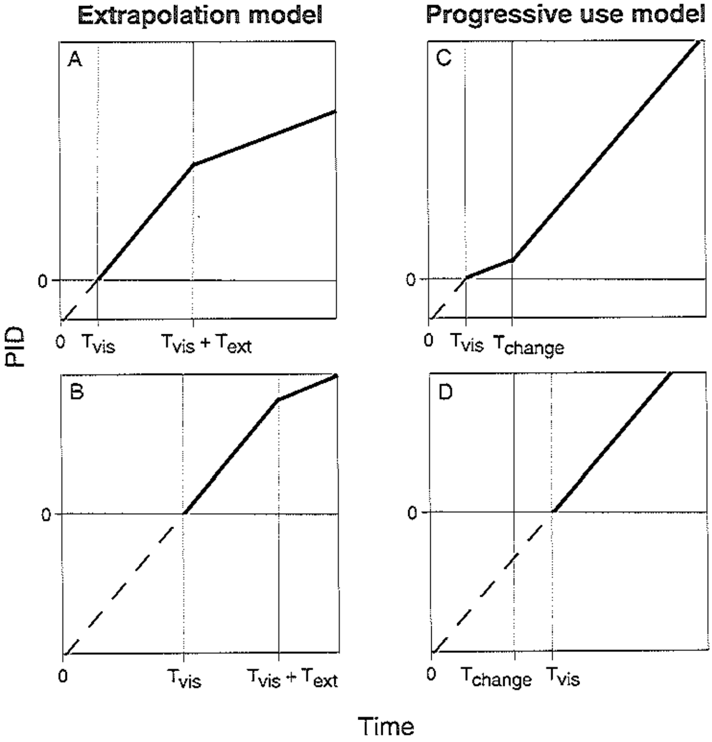

Figure 3-8. Schematic representation of the changing predicted invisible displacement (PID) as a function of time according to the extraplation model (A,B) and the model of progressive use of speed (C,D). A situation is depicted in which the spider speed is higher (steep line segments) than the default speed (flatter line segments). Dashed line segments indicate the visible spider movement, continuous line segments the extrapolation. Diagrams A and C represent the case in which the spider is visible briefly. In diagrams B and D the spider is visible longer. T_{ext} is the extrapolation time, T_{change} is the time after the start of the trial, at which the use of default speed changed into the use of actual speed.

Extrapolation hypothesis

It has long been known that the position of a dot which is flashed while the eyes are moving is misperceived in the direction of the eye movement (Mita et al. 1950; Mitrani et al. 1979). This does not only happen in the dark (Brenner and Cornelissen 2000). Brenner et al. (2001) proposed that this misperception arises because the perceived position of a target is determined by combining incoming retinal information with outgoing oculo-motor commands, without any consideration of neuronal or muscular delays[2]. This means that during pursuit the moving target is perceived at a position which the eye will look at, and the target will occupy, a fixed time (the extrapolation time) later. When dealing with targets that disappear while they are being pursued, the influence of the mislocalization is equivalent to using the actual speed during an extrapolation time, and a default speed during the remaining T_{invis}. This hypothesis predicts that spiders with a long T_{vis} will be hit better, not because they are visible for a long time, but because of the brief time they are invisible, so that the advantage of the predictive value of the misperception is relatively large.

To evaluate the extrapolation hypothesis, we transformed it into a model that quantitatively predicts the invisible displacement for each trial (visualized in Figure 3-8A and B). We assumed that subjects were pursuing the target with a gain of 1 by the time it disappeared. In order to find an exact value for the extrapolation time (T_{ext}) we fitted the model to the data. This also provided us with an additional test for the validity of the hypothesis, because we expected the fit to result in a value that corresponds to values of mislocalizations during pursuit eye movements. However, this additional test is not very critical because mislocalizations of 100 ms (Brenner et al. 2001), 153 ms (Mitrani and Dimitrov 1982) and 207 ms (Mitrani et al. 1979) have been found.

For each trial, we checked whether the extrapolation time exceeded the time between disappearance of the spider and arrival at the screen. If so, only the actual speed is used in guiding the hand (equation 3a). If not, the prediction is based on a mixture of actual and default speed (equation 3b).

If $T_{invis} < T_{ext}$:

$$PID = T_{invis} * v \tag{3a}$$

Otherwise:

$$PID = T_{ext} * v + (T_{invis} - T_{ext}) * v_d \tag{3b}$$

---

[2] The hypothesis of Brenner et al. (2001) predicts that the mislocalization starts at the time that the first oculo-motor command is given to pursue the target, before the actual eye movement has started.

A range of extrapolation times from 0 ms to the maximal T_{invis} were evaluated with the help of a program written in Matlab 5.0. The best fit of the model to the data was defined as that giving the lowest mean deviation of the used invisible displacements from the predicted invisible displacements (see methods). To estimate the reliability of the resulting parameter value, we calculated its standard error using the bootstrap method (Press et al. 1992) with 50 bootstrap trials. The analysis resulted in an extrapolation time of 156 ± 10 ms, which is a plausible value. The mean deviation of the data from the prediction was 0.32 cm (Figure 3-9A). This mean deviation is lower than the deviations found previously, but one should keep in mind that this value is the result of fitting one parameter.

Hypothesis of progressive use of speed

As already mentioned in the introduction, findings of van Donkelaar et al. (1992) suggest that if the reaction is delayed, so that subjects receive relatively long exposure to the target's speed before the hand starts to move, the direction in which the hand starts to move does depend on the target's speed. The hypothesis of progressive use of speed builds upon this finding. According to this hypothesis, the used target speed changes from a default speed to the actual one. If moving targets are visible too briefly, subjects do not have the opportunity to perceive the speed correctly, and therefore the final position of the hand will depend on a speed that lies between the default and the actual speed, depending on the exact T_{vis}.

Like the extrapolation hypothesis, this hypothesis combines default and actual target speed. However, the hypothesis of progressive use of speed predicts that subjects hit the long-visible spiders more successfully because they had more time to correctly perceive the speed of the target. Thus, according to this hypothesis, the T_{vis} and not the T_{invis} is the important factor.

To test the hypothesis of progressive use of speed, we again created a model which quantitatively predicts the invisible displacements (visualized in Figure 3-8C and D). We implemented one fixed time after the start of the trial, at which the use of default speed abruptly changed into the use of actual speed. To determine a value for this time (T_{change}) we used the same analysis as described in the section about the extrapolation hypothesis. A range from 0 ms to the maximal summed reaction and movement time was examined. Again, the average speed (11 cm/s) was taken to be the default speed. We used three different formulas depending on the timing.

If $T_{vis} > T_{change}$:

$$PID = T_{invis} * v \tag{4a}$$

Otherwise, if $RT+MT < T_{change}$:

$$PID = T_{invis} * v_d \tag{4b}$$

Otherwise:

$$PID = (T_{change} - T_{vis}) * v_d + (RT+MT - T_{change}) * v \tag{4c}$$

Equation 4a was used for all trials in which the spider was still visible at T_{change}. In this case, the predicted invisible displacement reflects the actual speed. Equation 4b was used for trials in which the movement ended before T_{change}. In these cases, subjects did not have enough time to use speed information in their movement. Thus, only the default speed will manifest itself in the predicted invisible displacement. Equation 4c was applied to the remaining trials. In these trials, both the default and the actual speed play a role. The default speed determines the guidance of the hand in the time between disappearance and T_{change}, and after T_{change}, the actual speed is used in guiding the hand. This means that if the spider is visible for a brief time, default speed determines the hitting position to a greater extent than if the T_{vis} is long.

The fit yielded a T_{change} of 307 ± 8 ms and a mean deviation from the data of 0.33 cm (Figure 3-9B). This model describes the data as well as the extrapolation model does (t_{129}=1.80, p=0.07), again with one fit parameter.

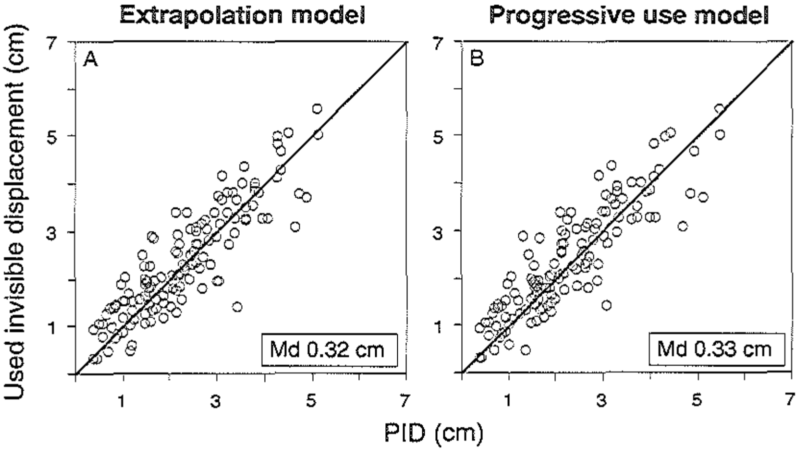

Figure 3-9. The used invisible displacement for each subject and each condition plotted against the invisible displacement predicted by **A** the extrapolation model and **B** the model of progressive use of speed.

We rejected the original hypotheses and proposed two new ones. Both the extrapolation hypothesis and the hypothesis of progressive use can better explain the present data than the hypotheses which only take the actual or the default speed into account (though that is not surprising since we added a free parameter). However, on the basis of this experiment we cannot decide for one of the two new hypotheses. We will evaluate them further in Experiment 2.

Experiment 2

We already mentioned a major difference between the extrapolation hypothesis and the hypothesis of progressive use. Both hypotheses predict that spiders with a long T_{vis}, i.e. spiders which are hit with a short T_{invis}, will be hit best, but for different reasons. We will use this difference in the following experiment.

According to the extrapolation hypothesis, the T_{vis} of a moving spider has no direct influence on performance. Spiders that have been visible for a long time and spiders that are visible briefly will in principle be hit equally well. However, the time between disappearance of the spider and the hand's arrival on the screen does make a difference. Subjects only benefit from the predictive value of the misperception for the duration of the extrapolation time. During the remaining time until the hand's arrival on the screen, the hand is guided by the default speed. Hence, increasing the T_{invis} beyond the extrapolation time will result in increasingly stronger dependency on the default speed and thus in increasingly worse performance.

In contrast, according to the hypothesis of progressive use of target speed, the time that the moving target is visible is the important variable. The shorter the T_{vis}, the more a subject has to rely on the default speed, because there was not enough time to perceive the real target speed. If a moving target is visible long enough to perceive the actual target speed, the time between the target's disappearance and the hand's arrival is not important. In this case, a long T_{invis} may result in more noise, but the same average results are predicted.

In Experiment 1, a longer T_{vis} automatically imposed a shorter T_{invis}. Therefore we do not know whether spiders which were visible for 350 ms were hit best because they had the longest T_{vis}, or because there was little time left after their disappearance. In the following experiment we tried to separate these issues. Subjects were asked to hit disappearing and non-disappearing spiders. The disappearing spiders were visible for either 150 or 442 ms, and disappeared at equal positions. In order to get the same T_{invis} for both values of T_{vis}, subjects had to wait for a tone before they were allowed to start moving their hand. The non-disappearing spiders were at the same position as those visible for 442 ms when the tone sounded.

The extrapolation hypothesis predicts that the two types of disappearing spiders will be hit at equal positions, with equal hitting errors, as these are invisible for the same time. Further, it predicts that hitting errors resulting from hitting non-disappearing spiders will be lower and independent of spider speed. The hypothesis of progressive use of speed predicts that hitting long-visible and non-disappearing spiders will result in equal hitting positions and hitting errors as they are both visible long enough to be able to use the correct speed. Additionally, it predicts that the errors resulting from hitting briefly visible spiders will be the highest and the most dependent on spider speed.

Methods

Materials and design

The materials are the same as in Experiment 1. The design is summarized in Figure 3-10. The spiders ran at 6, 12 or 18 cm/s. They did not disappear from view or were visible for 442 ms or 150 ms. If the spiders disappeared, they always disappeared 2 cm to the left of the starting position of the subject's hand. Subjects had to wait for a tone before they were allowed to react. In a pilot-study, we found that if the tone sounded an equal amount of time before disappearance, subjects reacted about 100 ms later when the T_{vis} was short than when it was long. As we wanted to get the same T_{invis} for each T_{vis}, we tried to cancel this effect by presenting the tone 142 ms before the briefly visible spider disappeared, and 42 ms before the disappearance of the longer visible spider. The tone presented with the non-disappearing spiders sounded after an equal amount of time as with the long-visible spiders, i.e., 400 ms after presentation onset. We also presented catch trials: spiders without a tone which were not to be hit. The results of these trials were not analyzed. These trials were included to train the subjects to only react after they heard the tone. During the whole experiment, if the subject started too soon (before the tone sounded or within 80 ms after the tone) or started moving in a catch trial, a message appeared on the screen that he or she had done so. Those trials were repeated later in the experiment.

The total number of trials was 180, of which 45 were catch trials (3 spider speeds * 15 trials) and 135 were experimental trials (3 T_{vis} * 3 spider speeds * 15 trials). The order was randomized.

Subjects and instruction

Ten volunteers from our department participated in the experiment. Seven of them had participated in the previous experiment. All subjects gave informed consent before participating in the experiment. Except for one, they were all right-handed. All subjects hit with their preferred hand. The instruction was the same as in Experiment 1, with the addition that they had to start the movement as soon as possible after they heard the tone. We also told the subjects about the trials in which there would be no tone and in which they were thus not allowed to hit the spider.

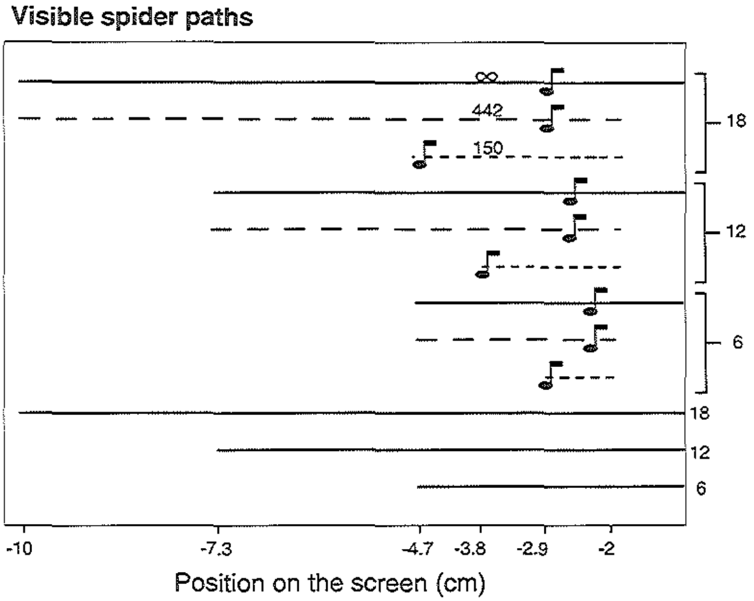

Figure 3-10. An overview of the design of Experiment 2. The lines represent the paths of the spiders relative to the hand's starting position during the time that they are visible. The T_{vis} (150 ms, 442 ms or continuous) is coded by the type of line, the spider speed (in cm/s) is indicated on the right of the paths. The notes indicate the position of the spider when the tone sounded.

Analysis

From a total of 1350 experimental trials, 3 were excluded from analysis for technical reasons. One additional trial was not analyzed because a subject needed more than 900 ms to move the hand from the starting position to the screen, and another was discarded because the subject missed the spider by more than 7 cm.

The reaction time is measured from the onset of the tone (instead of from the onset of the trial). As the spiders were (approximately) at the same position relative to the hand at the reaction time, we now measured the spider positions and hitting position relative to the projection on the screen of the starting position of the hand instead of relative to the starting position of the spider. For the analysis of the models, we assumed again that the default velocity equaled the average speed, now 12 cm/s. The statistical tests we used are the same as in Experiment 1.

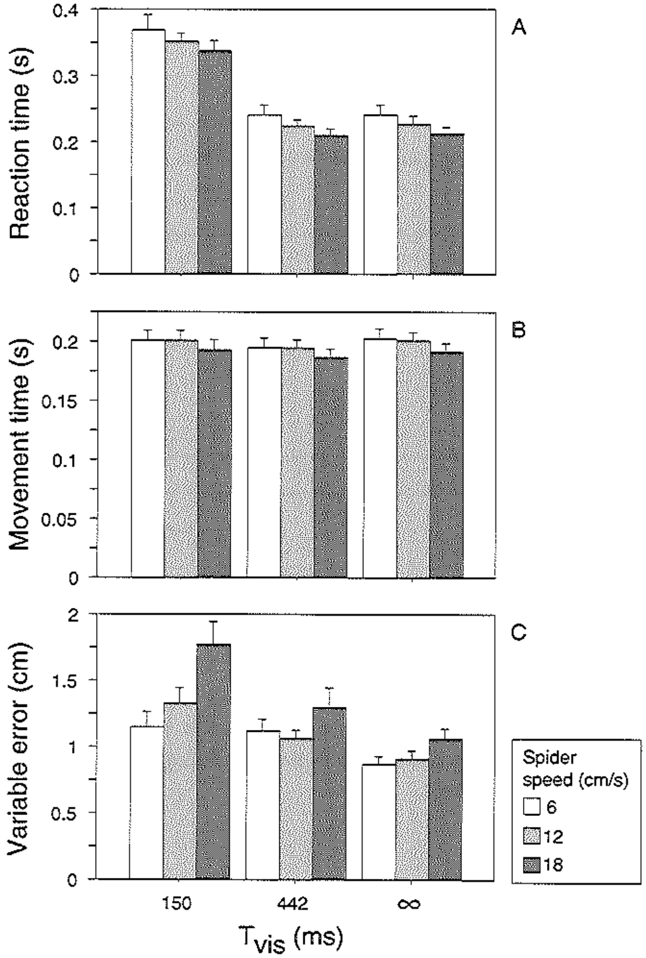

Figure 3-11. Reaction time (from the onset of the tone), movement time and variable error per T_{vis} and per spider speed. Error bars represent the standard error between subjects. **A** Reaction time decreases with spider speed and T_{vis}. **B** Movement time decreases with spider speed and is shortest when the spiders are visible for 442 ms. **C** Variable error increases with spider speed and decreases with T_{vis}.

Results

General characteristics

As we anticipated in our design, the reaction time (Figure 3-11A) depended on T_{vis} ($F_{(2,18)}=217.84$, $p<0.01$). It also depended on spider speed ($F_{(2,18)}=9.68$, $p<0.01$). The movement time (Figure 3-11B) was independent of the time that the spider was visible ($F_{(2,18)}=2.86$, $p=0.08$) and depended on spider speed ($F_{(2,18)}=18.33$, $p<0.01$). The variable error (Figure 3-11C) decreased with increasing T_{vis} ($F_{(2,18)}=19.53$, $p<0.01$) and became larger when the spiders ran faster ($F_{(2,18)}=4.86$, $p=0.02$).

In all, 75% of the spiders were hit successfully. As in Experiment 1, the number of hits depended on T_{vis}: 62% of the spiders with a T_{vis} of 150 ms were hit, 77% of the spiders which were visible for 442 ms were hit and 86% of the non-disappearing spiders were hit. Spiders running at 12 cm/s were hit best (81%). The percentages of successful hits towards fast and slow spiders were 68% en 76% respectively.

Results regarding the extrapolation hypothesis

Though we tried to prevent it, the T_{vis} was still negatively correlated with T_{invis}; the T_{invis} was on average 410 ms when spiders were visible for 150 ms and 376 ms when spiders were visible for 442 ms. However, if trials with a T_{invis} of 480 ms and longer are discarded, the average T_{invis} is about the same when briefly visible spiders are hit (368 ms) as when long-visible spiders are hit (367 ms). We decided to only use this selection of trials to compare the two types of disappearing spiders. As a result, the conditions with a T_{vis} of 150 ms are represented by 351 instead of 447 trials, and the conditions in which spiders were visible for 442 ms are represented by 422 instead of 450 trials.

Figure 3-12A shows the spider position and hitting position per T_{vis} and spider speed. There is a trend toward hitting longer visible spiders better. However, in accordance with the extrapolation hypothesis, the hitting positions and hitting errors were not significantly different for the different times that the spiders were visible (interaction T_{vis} and spider speed on hitting position $F_{(4,36)}=1.45$, $p=0.26$ and on hitting error $F_{(4,36)}=2.72$, $p=0.09$). Thus, the extrapolation hypothesis is not contradicted.

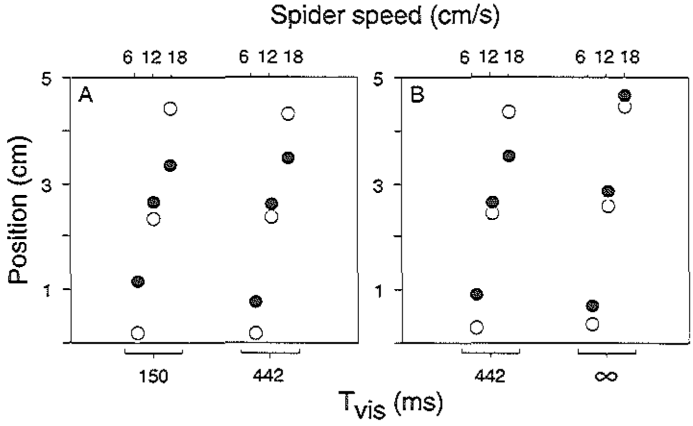

Figure 3-12. Spider positions (open circles) and hitting positions (solid circles) for each T_{vis} and each spider speed. Positions are measured relative to the projection of the hand's starting position. **A** A selection of the data is presented to achieve the same T_{invis} for spiders that are visible for 150 ms and 442 ms. The effect of spider speed on hitting position and hitting error was not significantly different for the different times that the spiders were visible. This is consistent with the predictions of the extrapolation hypothesis. **B** All responses to trials in which the spiders were either visible for 442 or did not disappear at all. Contrary to the predictions of the hypothesis of progressive use of speed, spiders that did not disappear were hit with a smaller hitting error which was less dependent on spider speed.

Results regarding the hypothesis of progressive use of speed

As there was no need to select the data to test the hypothesis of progressive use of speed, the values for a T_{vis} of 442 ms in Figure 3-12B are not identical to those in 3-12A. Figure 3-12B shows that long-visible spiders are not hit at the same positions as the non-disappearing spiders (interaction of spider speed and T_{vis} on hitting position: $F_{(4,36)}=12.21$, $p<0.01$). The hitting errors when hitting non-disappearing spiders are smaller and less dependent on target speed than when the spiders are visible for 442 ms (interaction spider speed and T_{vis}: $F_{(4,36)}=15.16$, $p<0.01$). These findings contradict the hypothesis of progressive use of speed.

Models

To compare the hypotheses quantitatively, we applied the models described for Experiment 1 to the data of Experiment 2. Only the trials with disappearing spiders were considered. The same computations and value for the parameter were used as in the first experiment. Figure 3-13 shows that the mean deviation is the same for both models ($t_{59}=0.13$, $p=0.90$).

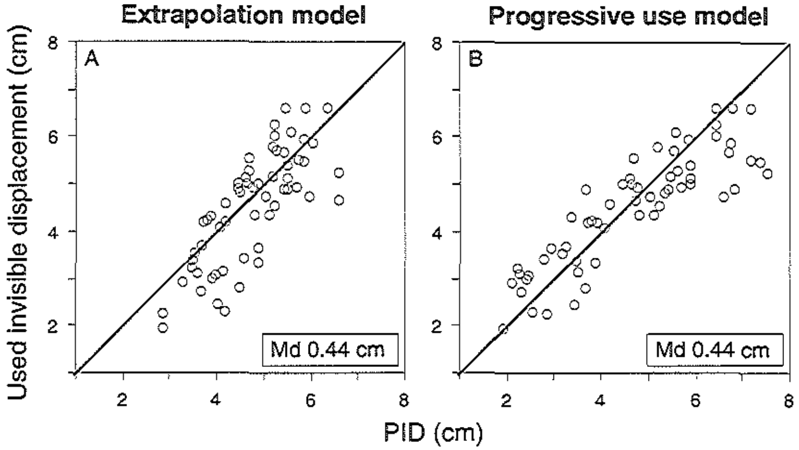

Figure 3-13. The used invisible displacement (ordinates) averaged for each subject and each condition plotted against the invisible displacement predicted by **A** the extrapolation model and **B** the model of progressive use of speed (abscissas), using the parameter values found in Experiment 1. The mean deviation of the points from the unity line is 0.44 cm for both models.

We also repeated the fitting procedure on the data of the disappearing spiders in Experiment 2 to see whether we would get the same parameter values for the models as in Experiment 1, and whether this would decrease the mean deviations. Instead of an extrapolation time of 156 ± 10 ms, we found that $T_{ext} = 243 \pm 11$ ms described these data best (mean deviation of 0.40 cm). However, the mean deviation was not significantly smaller than with T_{ext} =156 (mean deviation=0.44, t_{59}=1.14, p=0.26). Fitting the data to the model of progressive use of speed resulted in $T_{change} = 334 \pm 40$ ms (mean deviation=0.44 cm), which is close to the previously found T_{change} of 307 ± 8 ms. The mean deviation was not significantly lower than with T_{change} = 307 (mean deviation=0.44 cm as well, t_{59}=0.53, p=0.60). The mean deviations from the models using the parameter values from the fit to the data of Experiment 2 were also not significantly different (t_{59}=1.17, p=0.25).

The mean deviations between the used invisible displacements and the predicted ones in this experiment are higher for both models than in the first experiment. Still, the extrapolation model and the progressive use model perform much better than the simple models. For the data of Experiment 2, the actual speed model yields a mean deviation of 0.58 and the default speed model yields a mean deviation of 0.77.

Discussion

According to the hypothesis of progressive use of speed, subjects should be able to make optimal use of speed both when a non-disappearing spider is presented and when a spider is presented that is visible for a long time. However, these two types of spiders were hit at different positions. Hitting errors were lower and depended less on spider speed when spiders did not disappear than when they disappeared after being long visible. A second prediction of the hypothesis of progressive use of speed was that the subjects' use of speed would be better when the spider was visible long than when it was visible shortly, so that the hitting errors would become smaller and less dependent on spider speed. In contrast, we found that when T_{invis} was kept constant, an increase of T_{vis} from 150 to 442 ms did not change the hitting positions and hitting errors significantly. We thus reject this hypothesis.

The extrapolation hypothesis correctly predicted that T_{invis} would make a difference, so that hitting errors resulting from hitting non-disappearing spiders would be the lowest and the least dependent on spider speed. It also correctly predicted that the effect of speed on hitting positions and hitting errors would not depend on T_{vis} as long as the spiders were invisible for the same time. We conclude that the extent to which target speed has an effect on hitting position and error depends more on the time between the target's disappearance and the hit than on the time that the target is visible. This is in accordance with the extrapolation hypothesis.

Still, there is reason for caution before concluding that this hypothesis is a valid explanation. Firstly, though it is not significant, there is a trend for smaller hitting errors when spiders are visible for 442 ms than when they are visible for 150 ms, despite the equal T_{invis}. Secondly, the quantitative models did not favour the extrapolation hypothesis above the hypothesis of progressive use of speed. It is possible that this is due to the assumptions we made. Concerning the extrapolation hypothesis, it would be interesting to measure eye-movements during the interception of moving objects. The relation between the quality of the pursuit and the position of the hit could be explored. In the present study, we assumed that subjects always pursued the targets with a gain of 1, and that the first command to do so was given within the shortest T_{vis} (i.e., within 150 ms). However, Carl and Gellman (1987) found that targets moving at 10 deg/sec are only pursued smoothly after approximately 250 ms.

One could argue that both mechanisms play a role in guiding the hand to the point of interception. Together they will predict that a long T_{vis} as well as a short T_{invis} increase the chances of a successful hit. We constructed a hybrid model in which not only a time was implemented at which the used speed changed from the default into the actual speed, but also an extrapolation time that defines how long the actual speed continues to guide the hand after the target has disappeared. Whereas the T_{change} is defined as a fixed time after the start of the presentation, the T_{ext} is a fixed time after the disappearance of the spider. The used invisible displacements of Experiment 1 appeared to be described best by $T_{change} = 167$ ms and $T_{ext} = 166$ ms. The *PID*'s computed by the hybrid model are almost equal to the ones computed by the extrapolation model. This is because the value of T_{change} is only slightly higher than the T_{vis} of 150 ms, and lower than the other times that the spiders were visible, while the T_{ex} approximates the 156 ms extrapolation time we found earlier. Though the hybrid model has two fitted parameters instead of one, the mean deviation was 0.32 cm which is the same as the mean deviation of the extrapolation model. Thus, adding one parameter did not improve the fit to the data of Experiment 1. We therefore reject this model.

Although target speed is not used completely or correctly in guiding the hand to the interception point of a moving target, Experiment 1 shows that it does play a role. In Experiment 2 we tested two more specific hypotheses that differed in the nature of the influence of target speed. According to the extrapolation hypothesis, speed has an indirect effect through affecting the perceived position of the target. According to the hypothesis of progressive use of speed, subjects take target speed itself into account while guiding their hand. The extrapolation hypothesis explains better how the hitting position is determined than the hypothesis of progressive use of speed, but it was not supported unequivocally. In a third experiment we use a different approach to see whether we can find additional support for the idea that the measured effect of speed is caused by a speed-related misperception of the target rather than a direct use of speed in guiding the hand.

Experiment 3

Again subjects hit briefly visible spiders running from the left to the right, but this time we sometimes moved the background to manipulate the perceived speed of the spiders. If the background moves to the left, the perceived motion of the spider is faster than if it moves to the right (Smeets and Brenner 1995a). Thus, if subjects use perceived speed itself to guide their hand, they should hit more to the right (ahead of the invisible spider) if the background moves to the left than if the background moves to the right.

Methods

Materials and design

The materials are the same as in Experiment 1. We used a short T_{vis} of 200 ms so that possible differences in hitting positions between the conditions would become more obvious. We knew from Experiment 1 that 200 ms is long enough to ensure that target speed has an effect. Both the spiders and the background disappeared, because we wanted to manipulate the perceived speed of the spider and to reduce possible effects of a moving background after the spider had disappeared. When the rod arrived at the screen, the background and the spider appeared again to give the subject feedback as in the other experiments. During the feedback, the background was static.

The starting point of all spiders was 8 cm to the left of the starting position of the subject's hand. The spiders ran at 6, 12, 18 or 24 cm/s. Spiders running at 12 or 18 cm/s always ran across a background that was moving at 6 cm/s, either to the left or to the right. The background started to move at the same time as the running spider appeared. The background was static when the spiders ran at 6 or 24 cm/s. This yielded 6 conditions. We presented 15 trials per condition, which results in a total of 90 trials for each subject. The order was randomized.

Subjects and instruction

Ten volunteers from our department participated in the experiment, after giving informed consent. Six of them had participated in both previous experiments and one had only participated in Experiment 2. One subject was left-handed, the rest were right-handed. They all hit with their preferred hand. The instruction was the same as before. We told the subjects that the background could move (though this was not necessary because the background's motion was clearly visible).

Analysis

From the total of 900 trials, 2 were excluded from analysis for technical reasons. We did not define any new measures to describe the results of this experiment.

We performed repeated measures analyses of variance for the factor spider speed on averages from the complete dataset for each subject and spider speed. Separate repeated measures analyses of variance were performed on the subset of data in which the background moved. These had target speed and background direction as factors.

Results

General characteristics

Reaction time (Figure 3-14A) and movement time (Figure 3-14B) decreased with increasing spider speed, as they had in the previous experiments ($F_{(3,27)}=6.32$ and $F_{(3,27)}=46.54$ respectively, both $p<0.01$). Direction of background motion did not affect reaction time and movement time (respectively $F_{(1,9)}<1.0$, p=0.95 and $F_{(1,9)}=1.46$, p=0.26). There was a significant effect of spider speed on variable hitting error ($F_{(3,27)}=3.40$, p=0.03) but this was not systematic (Figure 3-14C). Direction of background motion significantly affected the variable hitting error as well ($F_{(1,9)}=7.00$, p=0.03).

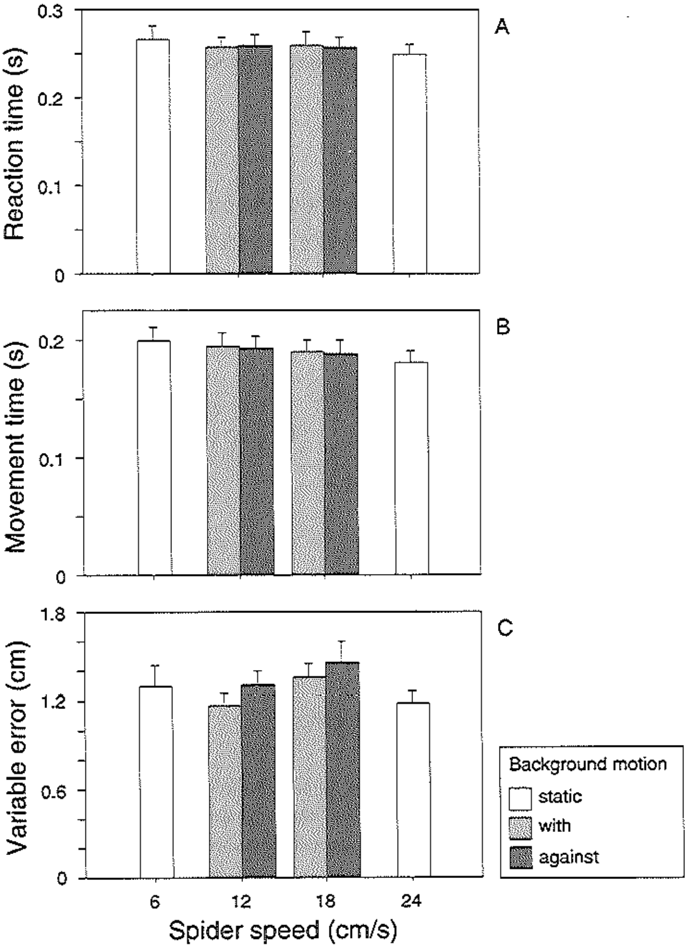

Figure 3-14. Reaction time, movement time and variable error for each spider speed and background motion in Experiment 3. Error bars represent the standard error between subjects. **A**, **B** Reaction time and movement time both decrease with spider speed and are independent of background motion. **C** Variable error did not systematically depend on spider speed. Variable error was higher when the background moved in the opposite direction than the spider (against) than when it moved in the same direction (with).

Of all spiders, 65% were hit successfully. In contrast to the previous experiments it appeared that fast spiders, in terms of absolute and apparent speed, were easiest to hit. From the highest to the lowest spider speed, the percentages of hits were 76%, 69%, 61% and 54%. Of the apparently faster spiders (i.e. with a background moving in the opposite direction), 67% were hit successfully. 63% of the apparently slower spiders were hit. Spiders running over a static background were hit in 65% of the trials. Note that the average hitting percentage was the same when the background moved as when it was static.

Hitting positions

Figure 3-15 shows the hitting position and spider position for each spider speed and for each background motion. Spider speed had a significant effect on hitting position and hitting error ($F_{(1,9)}$=65.53 and $F_{(1,9)}$=39.87 respectively, p-values <0.01). Direction of background motion did not significantly influence hitting position or hitting error ($F_{(1,9)}$=2.92, p=0.12 and $F_{(1,9)}$=2.69, p=0.14).

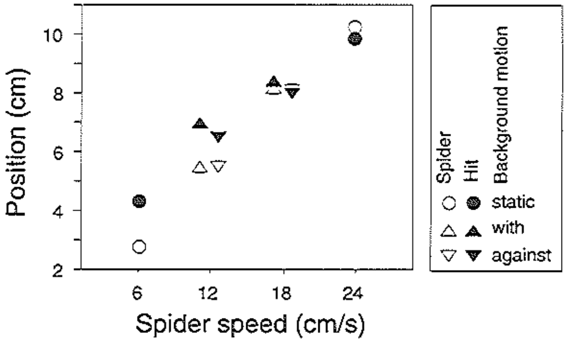

Figure 3-15. Spider position and hitting position (relative to the start of the spider's movement) for each speed and background motion. Subjects do not hit further behind spiders when the background moved in the same direction as the target (with) than when it moved in the opposite direction (against). This contradicts the idea that subjects use perceived speed, because the spider appears to be slower if the background moves in the same direction.

Discussion

If subjects had used perceived speed in hitting moving spiders, they would have hit further in front of the disappearing point when the spider appeared to move faster than when it appeared to move more slowly. In contrast, we found no effect of the direction of background motion on hitting position and hitting error. The trend was even the opposite;

subjects tended to hit further to the left (i.e., behind the spider) when the background moved to the left (and the spider appeared to move faster) than when it moved to the right. This trend might be explained by the finding that for brief presentations (tested for 100 ms or less) the perceived position shifts in the direction of the moving background (Brenner and Smeets 1997), possibly because the egocentric reference system is affected by a moving background (Mohrmann-Lendla and Fleischer 1991). Consequently, if only target position is used, subjects may hit a bit more to the left if the background moves to the left and more to the right if the background moves to the right.

In conclusion, the results of Experiment 3 support the suggestion that target speed is not used in guiding the hand when hitting moving objects. They are consistent with the idea that only target position and a default speed are used.

In the previous experiments, subjects made the smallest systematic errors when hitting spiders running at the average speed (Figure 3-6 and Figure 3-12), suggesting that the average spider speed is not a bad estimate for a hypothetical default speed. In the present experiment, subjects hit spiders running at 18 cm/s best (Figure 3-15). We have no explanation for this.

Summary and general discussion

In Experiment 1 we tested whether subjects use target speed or whether they only use target position and a default speed in guiding their hand to intercept moving targets. We observed that there was a partial effect of target speed on the hitting position. The magnitude of the effect depended on the time that the target was visible (or the time between the target's disappearance and the hit). In Experiment 2 we tested specific, refined versions of the hypotheses that either target position and a default speed or the actual speed is used. According to the extrapolation hypothesis subjects use the perceived position and a default speed, and the effect of the target's actual speed occurs via misperception of the target position. It predicts that the effect of target speed will become weaker with a longer T_{invis}. According to the hypothesis of progressive use of speed, it takes longer to use the actual speed, so that the longer the T_{vis}, the better subjects are able to use speed. We found that only the T_{invis} significantly influenced the effect of target speed. Thus, the extrapolation hypothesis was favoured above the hypothesis of progressive use of speed. However, as the evidence was not overwhelming we performed a third experiment in which the general question whether subjects use only position and a default speed or the actual (perceived) speed was tested in another way. The perceived speed was manipulated by moving the background. The results indicated that the hitting positions were not affected by illusory target speed.

At first sight, our conclusion that target speed is not used in guiding the hand to the place of interception seems to be in conflict with the results of Experiment 1 and 2 in which an effect of target speed on hitting positions was found. However, the extrapolation model (that we tested in Experiment 2) is an example of how target speed can have an indirect effect on the hitting position. Target speed influences the perceived position of the moving target so that if that misperceived target position is used, you will find an effect of target speed. This influence is fundamentally different from directly using target speed because it cannot be used to make predictions for arbitrary moments. In Experiment 3 we moved the background so that the target speed was misperceived. This did not affect the hitting positions, as would be expected on the basis of the hypothesis that you do not use target speed but target position.

Our results indicate that perceived target speed is not used in guiding the hand to the position of interception. Previous research indicates that it is used in guiding the timing of the hand. More specifically, subjects move faster to fast targets than to slow ones (e.g. Bootsma and van Wieringen 1990; Brouwer et al. 2000; Wallace et al. 1992; influence of target speed on movement time in the present study). This is also observed when subjects are asked to always move as quickly as possible and when the perceived speed is manipulated by moving the background (Smeets and Brenner, 1995a). This suggests that the information used to guide the hand's timing differs from the information used to determine the hand's spatial trajectory. It may therefore be impossible to understand interception as a continuous coupling between action and the changing visual information, without distinguishing between spatial and temporal aspects, as these may in fact be controlled separately to a certain extent.

Chapter 4

Can acceleration be used in interception?

The part until 'A possible way to determine the correct running direction in catching balls' is in press as: Brouwer. A.. Brenner, E., & Smeets, J. B. J. Perception of acceleration with short presentation times: Can acceleration be used in interception? *Perception and Psychophysics.*

We thank Raoul Oudejans and Claire Michaels for providing us with the data of their experiment.

Abstract

To investigate whether visual judgements of acceleration could be used for intercepting moving targets, we determined how well subjects can detect acceleration when the presentation time is short. In a differential judgement task, two dots were presented successively. One dot accelerated and the other decelerated. Subjects had to indicate which of the two accelerated. In an absolute judgement task, subjects had to adjust the motion of a dot so that it appeared to move at a constant velocity.

The results for the two tasks were similar. For most subjects we could determine a detection threshold even when the presentation time was only 300 ms. However, an analysis of these thresholds suggests that subjects did not detect the acceleration itself but that they detected that a target had accelerated on the basis of the change in velocity between the beginning and the end of the presentation. A change of about 25% was needed to detect acceleration with reasonable confidence.

Perhaps the simplest use of acceleration for interception is distinguishing between acceleration and deceleration of the projection of an approaching ball to determine whether one has to run backward or forward to catch it. We examined the results of a real ball-catching task (Oudejans, Michaels & Bakker, 1997) and found that subjects reacted before acceleration could have been detected. We conclude that acceleration is not used in this simple manner to intercept moving targets. We propose an alternative way to determine the correct running direction in catching balls, based on the use of expansion and angular velocity.

Introduction

In the present study we investigate the possibility of using information about targets' angular acceleration[3] when intercepting moving targets. For succesful interception it is necessary to take the changing position of the moving target into account. Information about the target's acceleration could therefore be helpful. When the target moves in a frontal plane (as was the case in the interception studies of Bairstow, 1987; van Donkelaar, Lee & Gellman, 1992; Brouwer, Brenner & Smeets, 2000) any acceleration of the target will result in an (approximately) equivalent optic angular acceleration. Both Rosenbaum (1975) and Port, Lee, Dassonville and Georgopoulos (1997) examined whether subjects took acceleration into account when predicting the time at which a target, moving in a frontal plane, reached a certain point in space. Rosenbaum presented accelerating targets moving from left to right, or vice versa. The targets disappeared behind a mask, and the task was to indicate when they passed a mark on the mask. Port et al. let their subjects intercept accelerating targets on a computer screen with a cursor controlled by a computer mouse. They were to intercept the targets within a prescribed area on the screen. Whereas Rosenbaum concluded that subjects used acceleration, Port et al. concluded that they did not. Perhaps subjects cannot use acceleration in a real interception task such as in Port et al., whereas they can use it in a more perceptual or cognitive task such as that of Rosenbaum. Another possible reason for the difference is that the accelerations of the stimuli used by Port et al. may not have been large enough. They were well above threshold levels found in other studies, but the durations of the stimuli in those studies were long which, as we will argue later, can make a difference.

The relation between the acceleration of the target and the optic angular acceleration is not as simple when objects approach an observer, as is the case in catching fly balls. Nevertheless, even in this task detecting angular acceleration can be helpful, though not for predicting when the target will be at a certain position. The sign of the angular acceleration of the vertical motion of the ball's projection indicates whether the ball will land ahead of or behind the observer (Chapman, 1968). Thus, subjects could in principle use angular acceleration to determine whether they should run forward or backward. Some research suggests that this strategy is used (Babler & Dannemiller, 1993; McLeod & Dienes, 1996; Michaels & Oudejans, 1992, Lenoir et al; 1999) and other research claims it is not used (Todd, 1981; McBeath, Shaffer & Kaiser, 1995). We will elaborate on this issue in the discussion.

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[3] We will use the term 'acceleration' to refer to both acceleration and deceleration. To distinguish between the two, we will use 'positive' acceleration when the speed increases and 'negative' acceleration (or deceleration) when it decreases.

It is difficult to determine whether humans perceive angular acceleration well enough to be able to use it in interception. Previous studies report very different detection thresholds for acceleration (Gottsdanker, Frick & Lockard, 1961; Schmerler, 1976; Calderone & Kaiser, 1989; Babler & Dannemiller, 1993). Moreover, the total change of velocity during a presentation predicts the detection threshold better than does the rate of change in velocity (Gottsdanker, Frick & Lockard, 1961; Schmerler, 1976). Thus subjects appear to be unable to perceive the rate of change in velocity (the acceleration) and detect that the velocity has changed during the presentation instead. In the following we will summarize some of these findings.

Gottsdanker et al. (1961) asked their subjects to discriminate between an accelerating dot and a dot moving at a constant velocity. The dots were presented successively and there were separate sessions for positive and negative acceleration. Gottsdanker et al. reported a wide range of 75%-correct thresholds. The thresholds varied between 26% and 157% change in velocity (hereafter defined as the difference between the final and initial velocity divided by the average velocity). The highest thresholds were found with the shortest presentation time, which was 450 ms. Schmerler's (1976) subjects categorized stimuli as positive, negative or no acceleration. There were separate sessions in which positively accelerating stimuli were presented together with non-accelerating stimuli, and ones in which negatively accelerating stimuli were presented with non-accelerating stimuli. The threshold was defined as the ratio between initial and final velocity that was required for 50% of the responses to be 'positive acceleration' in the former sessions, and 50% of the responses to be 'negative acceleration' in the latter sessions. The average threshold was a ratio of about 2.7 (which corresponds to a 92% change in velocity). Calderone and Kaiser (1989) used a task whereby subjects had to indicate whether or not a small square accelerated positively. In a separate condition they had to indicate whether or not it decelerated. Calderone and Kaiser (1989) found a 75%-correct threshold of about 60% change in velocity. Subjects of Babler and Dannemiller (1993) indicated whether a dot accelerated positively or negatively. The 75%-correct threshold was approximately 20% change in velocity.

Beside the fact that there is no agreement about threshold values between these studies, there is another reason why it is difficult to use these thresholds to determine whether acceleration is perceived well enough to be used in interception. Most stimuli in these studies were presented for one second or longer. In interception tasks it is often necessary to react quickly. Thus, in order to be useful, acceleration has to be detected quickly. In the present study we determined acceleration thresholds for presentation times that are shorter than a second.

We used two methods to determine acceleration thresholds; a differential judgement method and an absolute judgement method. In the differential judgement method we successively presented the subjects with a positively and a negatively accelerating dot. The subjects had to indicate whether the first or the second moving dot accelerated positively. We used a staircase procedure to find a 75%-correct threshold. In the absolute judgement method, subjects had to adjust the acceleration of a moving dot so that the dot moved at a constant speed. This method has the advantage of revealing possible biases in what is perceived as a constant speed, which will affect interception behaviour if acceleration is used.

Methods

Materials and design

The stimuli were presented on a monitor at 120 Hz. The spatial resolution was 815 by 611 pixels (39.2 by 29.3 cm) and was enhanced with anti-aliasing techniques. The viewing distance was 50 cm (thus 1 cm on the screen corresponds to about 1.1 degrees of visual angle). A chin- and forehead rest was used to keep the viewing distance constant. The experiment took place in a normally illuminated room.

Subjects viewed a gray background with two 4-cm red squares. A 4-mm diameter black dot appeared from behind the left square, moved to the right, and disappeared behind the right square. The dot was presented for 300, 600 or 900 ms and had a mean velocity of 3, 13 or 23 cm/s. This resulted in 9 conditions (3 presentation times * 3 average velocities). The distances traveled by the dot (i.e. the separation between the red squares) necessarily differed between the conditions. Since we kept the average velocity and the duration constant within a condition, a change in acceleration resulted in a change of both the initial and the final velocity. The conditions were blocked and the block order was randomized across subjects.

We tried to create circumstances that are favorable for perception of acceleration. The two squares and the edges of the monitor were clearly visible and served as landmarks. Such landmarks have been shown to facilitate the perception of motion (e.g. Smeets & Brenner, 1994). Further, the design was blocked, so that the average speed was known in advance. Pursuit eye movements may be important in perceiving acceleration, and a predictable average speed will probably improve the quality of pursuit. The thresholds we obtain will therefore presumably be lower than those obtained in more natural situations.

Differential judgement task

Every condition was tested using a separate block of 50 trials. Two dots were presented in each trial, with an inter-stimulus interval of 1000 ms. One of the dots accelerated positively and the other negatively, at the same rate. The task of the subject was to indicate whether the first or the second stimulus accelerated positively (by pressing the appropriate mouse button).

We used a staircase method to find the acceleration at which subjects responded correctly on 75% of the trials. On the first trial the dots moved at the maximal possible acceleration (defined by a zero starting velocity of one dot and a zero ending velocity of the other). The step size decreased logarithmically with acceleration rate, so that after each correct choice the acceleration was 80% of its previous value. After an error the acceleration was increased by three such steps (to 195% of its previous value).

Absolute judgement task

Every condition was represented by a block of 20 trials. In each trial, one dot was presented repeatedly with a 1000 ms interval between presentations. Subjects had to adjust the dot's acceleration using a computer mouse until it appeared to move at a constant velocity. We told them that moving the mouse to the right would increase the dot's acceleration and moving the mouse to the left would decrease its acceleration. Subjects were allowed to take as long as they liked (and thus to see the stimulus as often as they liked) to make their settings. Once they were satisfied they pressed a mouse button. This started the next trial. The initial acceleration was chosen at random from the range of possible accelerations for that condition (limited by starting and ending velocities of 0).

Analysis

Differential judgement task

For each subject and each condition the average percentage correct per value of acceleration was plotted as a function of the log of acceleration. The threshold was determined by fitting a sigmoid through these points and taking the intersection with the 75%-correct line. The points were weighted by the square root of the number of times they were presented. The sigmoid was defined as:

$$y = 50 + \frac{50}{1 + e^{a-bx}}$$

where x is log acceleration and y is the average percentage correct. The values of a (the shift across the abscissa) and b (the steepness of the curve) were fitted. This sigmoid starts at y=50 (chance level) for no acceleration and tends toward y=100 (always correct) for large accelerations.

As already mentioned in the introduction, it has been proposed that acceleration itself is not perceived, but that it is detected by comparing the initial and final velocity. We therefore also converted the thresholds into percentages of change in velocity (the difference between the final and initial velocity divided by the mean velocity; Calderone & Kaiser, 1989; Babler & Dannemiller, 1993). For this calculation, we considered the dot's velocity when it was half occluded by each of the squares as its initial or final velocity.

Absolute judgement task

The average setting will reveal any bias in the perception of acceleration. However, a correct average setting (zero) does not tell us that acceleration is perceived well; it will also be about zero if subjects set the acceleration values at random. We used the standard deviation of the settings per subject and condition as acceleration thresholds. These thresholds were also converted into percentages of change in velocity.

Statistical tests

We used repeated measures analyses of variance to examine the effect of presentation time and of average velocity on the thresholds expressed both as the logarithm of acceleration in cm/s^2 and as the percentage of change in velocity. The biases of the settings were evaluated with one sample t-tests. The input for these tests was the average setting for each subject and condition. We took $p<0.05$ as the level of significance.

Subjects

Ten observers participated. Three of them were the authors. The other subjects were naive about the purpose of the experiment. Subjects could take a break between blocks.

We excluded the results of three (naive) subjects in both tasks from analysis because these subjects could not discriminate between the maximal accelerations in one or more conditions of the differential judgement task (operationalised as this maximal value having been presented more than ten times, which made it impossible to determine a threshold). Excluding the subjects who are poorest at perceiving accelerations contributes to finding low thresholds.

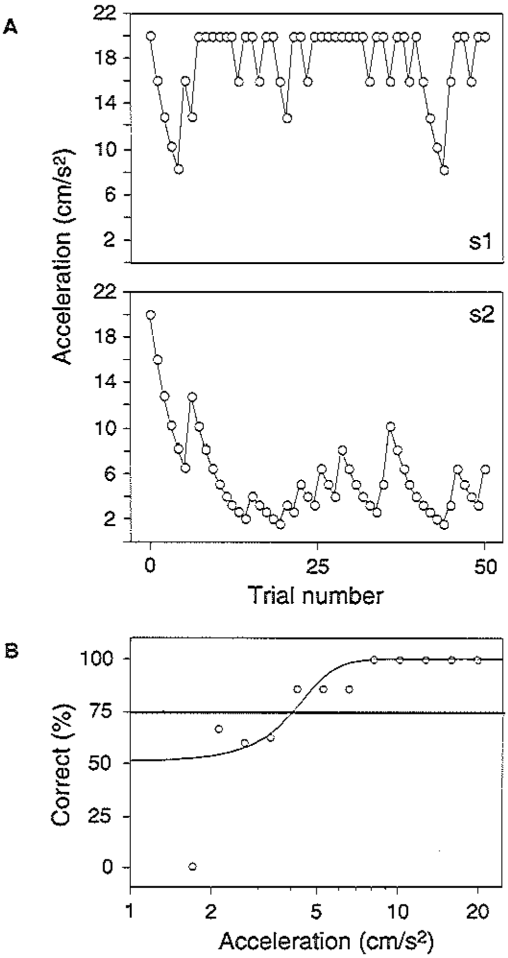

Figure 4-1. Examples of two subjects' staircases (A) and one subject's fitted sigmoid (B) in the condition with 300 ms presentation time and a mean velocity of 3 cm/s. When the subject labels the correct dot as positively accelerating, the acceleration of the dots in the next trial is one step lower. When he or she makes a mistake, the acceleration increases three steps. Subject s1 is unable to distinguish between positive and negative acceleration even at the extremes. This subject was one of the three whom we excluded from further analysis. Subject s2 reaches a threshold value. The threshold is defined as the acceleration where the fitted sigmoid crosses the 75% correct line.

Results

Differential judgement task

Figure 4-1A shows the raw staircases of a subject who cannot distinguish between positive and negative acceleration (s1) and a subject who can (s2) in the condition of 300 ms presentation time and 3 cm/s average velocity. Even at the maximal acceleration of 20 cm/s^2, subject s1 does not respond above chance. Thus, a threshold cannot be determined. This subject is one of the three who were excluded from further analysis. Figure 4-1B shows the sigmoid fit for subject s2.

The mean acceleration thresholds (Figure 4-2A) clearly depend on presentation time ($F_{(2,12)}$=177.01, p<0.01) and mean velocity ($F_{(2,12)}$=59.74, p<0.01); the longer the dot is visible and the slower its mean velocity, the lower the threshold. In Figure 4-2B the thresholds are expressed as percentages of change in velocity. When described in this manner the thresholds still depend on presentation time ($F_{(2,12)}$=9.57, p<0.01), but less conspicuously than when they are described as accelerations. Thresholds expressed as percentages of change in velocity are independent of mean velocity ($F_{(2,12)}$=1.79, p=0.21). The average threshold is about 25% change in velocity.

Absolute judgement task

Figure 4-3 shows the average setting that was judged as having a constant velocity in each condition. There was only a significant bias in the condition with a presentation time of 300 ms and a mean velocity of 3 cm/s (t_6=-3.26, p=0.02). This bias is negative: a decelerating dot is perceived to move at a constant velocity.

The thresholds found with the absolute judgement method (Figure 4-4) are very similar to the ones found with the differential judgement method (Figure 4-2). When expressed as accelerations, they decrease with presentation time ($F_{(2,12)}$=169.70, p<0.01) and increase with mean velocity ($F_{(2,12)}$=158.01, p<0.01) (Figure 4-4A). When expressed as percentages of change in velocity (Figure 4-4B) the thresholds are independent of both presentation time ($F_{(2,12)}$=1.62, p=0.24) and mean velocity ($F_{(2,12)}$=0.28, p=0.76). The average threshold found with the absolute judgement method is about 25% change in velocity, the same as found with the differential judgement method.

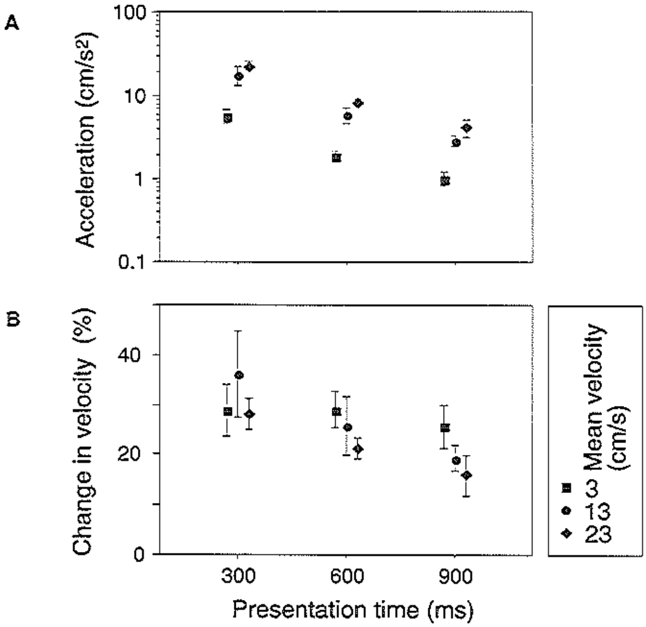

Figure 4-2. Results of the differential judgement task. Mean thresholds of 7 subjects with between subject standard errors for each condition. The thresholds are expressed both as rate of change in velocity (A) and as percentage of change in velocity (B). In the former unit the thresholds depend on both presentation time and mean velocity. In the latter they only depend on presentation time.

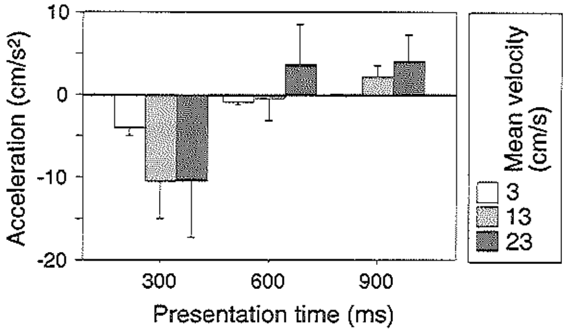

Figure 4-3. Average settings for each condition in the absolute judgement task. Error bars represent between subject standard errors. Only the average setting in the 300 ms - 3 cm/s condition is significantly different from zero.

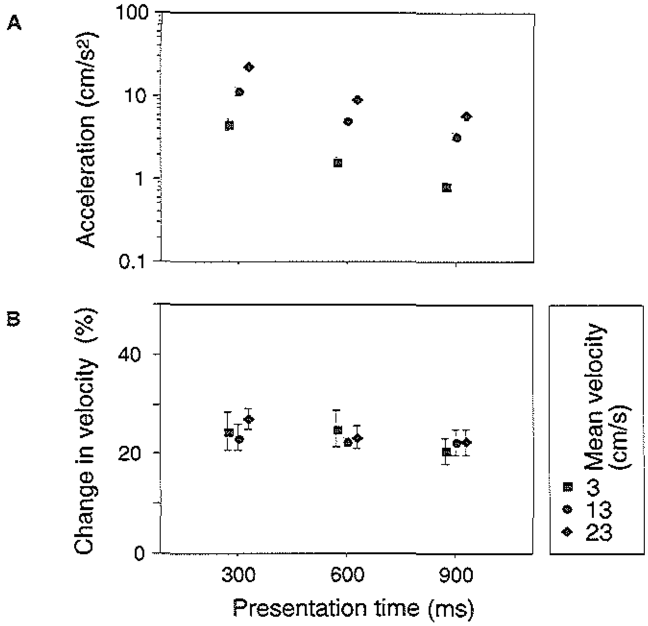

Figure 4-4. Results of the absolute judgement task. Mean thresholds of 7 subjects with between subject standard errors for each condition. The thresholds are expressed both as rate of change in velocity (A) and as percentage of change in velocity (B). Thresholds depend on presentation time and mean velocity when expressed as rate of velocity change. Expressed as percentage of change in velocity the thresholds are independent of both presentation time and mean velocity.

Discussion

The settings in the absolute judgement task revealed a negative bias for the shortest presentation time (though only significant for the slowest targets). This is surprising as two findings led us to expect a positive bias. Firstly, Runeson (1974) found that targets that are moving at a constant speed appear to move faster at the beginning of the movement. If subjects had perceived constantly moving dots as decelerating for such reasons, they would have set the dot to accelerate positively in order to see it moving at a constant speed. Secondly, it is reported that negative acceleration is easier to detect than positive acceleration, at least if the stimulus moves horizontally (Gottsdanker, Frick & Lockard, 1961; Schmerler, 1976; Babler & Dannemiller, 1993; Calderone & Kaiser, 1989). Such an asymmetry between the detection of positive and negative acceleration, whereby subjects are better of avoiding the latter, could lead to a positive bias in the setting.

We found that most subjects could distinguish between positive and negative acceleration when targets were presented for as short as 300 ms. In accordance with earlier results for long presentation times (Gottsdanker et al., 1961; Schmerler, 1976), we observed that when the presentation times are short, acceleration thresholds strongly depend on the presentation time and on the mean velocity of the dot. This was so for both our methods.

The results of both methods also agreed that thresholds were more constant over different mean velocities and presentation times when they were expressed as changes in velocity than when they were expressed as acceleration values. This too is consistent with the results of Schmerler (1976), Gottsdanker at al. (1961) and Calderone and Kaiser (1989) for longer stimuli presentations. Thus subjects probably perceive the difference between the positively and negatively accelerating stimuli by comparing the initial and final velocities instead of by perceiving the acceleration itself. We will therefore further evaluate acceleration thresholds in terms of the percentages of change in velocity.

The value of the average threshold is approximately 25% change in velocity, regardless of the method used. We had not expected the values to be so similar as both the tasks and the definition of the thresholds differed. In the differential judgement task subjects compared positively and negatively accelerating dots, while in the absolute judgement task they had to detect whether there was any acceleration present, and if so to adjust the dot's motion. The threshold found using the differential judgement task is the acceleration at which subjects answer correctly in 75% of the cases when they have to distinguish positive from negative acceleration. The threshold found using the absolute judgement task is the standard deviation of the acceleration settings when subjects try to make the dot move at a constant velocity. Both values probably underestimate human perceptual thresholds. In the differential judgement task we cannot tell whether subjects compared the initial and final velocities of a single dot, or whether they compared the final or initial velocities of the two dots. The compared velocities are equal in the two cases. However, comparing velocities between two dots might be easier because a change in velocity is easier to detect if there is an interval between the presentations of the two velocities (Monen and Brenner, 1994). In the absolute judgement task subjects saw the dots several times, which may reduce the thresholds.

The average 75%-correct threshold found by Babler and Dannemiller (1993) was about 20% change in velocity, which comes close to our average acceleration threshold of 25%. Theirs is the best reported performance. As described in the introduction, other thresholds found in the literature (Calderone & Kaiser, 1989; Schmerler, 1976; Gottsdanker, Frick & Lockard, 1961) are substantially higher than the ones that Babler and Dannemiller and that we found. Babler and Dannemiller attributed the difference between their threshold and the ones found by others to experimental differences, one of which applies to our experiment as well. In the experiment of Babler and Dannemiller, and in our differential judgement task, subjects had to classify stimuli as positively accelerating or decelerating, without the option of them moving at a constant velocity (which was an option in the other experiments).

We already mentioned additional possible causes for our thresholds being low. We designed our stimuli in such a way that the perception of acceleration would be relatively easy (see Methods). We excluded the three subjects with the highest thresholds (because their thresholds were beyond the reach of what could be measured for the shortest presentation times). In the differential judgement task subjects could have compared final or initial velocities between dots. In the absolute judgement task, subjects could see the stimuli as often as they liked. A final reason for our thresholds being relatively low is the way we defined the initial and final velocity to calculate the percentage of change in velocity. Of course, the physical final and initial velocities are only present for an infinitely short time, whereas their measurement by our visual system takes time. We arbitrarily took the velocities when the dot was half visible as the initial and final velocity. In other studies the instantaneous initial and final velocity were taken to compute the percentage of change in velocity, which will result in slightly higher thresholds.

Use of acceleration for intercepting targets moving in a frontal plane

We confirmed, for short presentation times, that the amount of change in velocity is critical for detecting acceleration, irrespective of how long it takes for that change to occur (i.e. irrespective of the acceleration). It is therefore unlikely that judgements of the acceleration itself are involved in intercepting accelerating objects moving across a frontal plane. Still, subjects could take acceleration into account in a less precise way, for example by moving faster or reacting earlier to positively accelerating objects. In the study by Port, Lee, Dassonville and Georgopoulos (1997) that was mentioned in the introduction, subjects arrived at the interception zone too early when targets decelerated and too late when they accelerated positively. Port et al. (1997) concluded that information about acceleration was not used. They claim that the accelerations they used were above the detection threshold found with long presented stimuli. In the present study, we did not find a higher threshold for shortly presented stimuli, so one would say that the accelerations Port et al. (1997) presented were high enough to be detected. However, in claiming that the accelerations they used were above threshold, Port et al. (1997) considered the change in velocity between the stimulus' initial and final velocity (in the interception zone). They should have considered the change in velocity between the beginning of the target motion and the time that the movement was planned (or last adjusted). As we do not know this time, it is impossible to determine this change in velocity. To get an indication, we computed the changes in velocity for different stimuli at the reaction time. We did so for the subject who (on average) reacted earliest. At the reaction time the change in velocity of all different kinds of positively accelerating stimuli was well above 25%. Of the decelerating stimuli only two out of six stimuli exceeded the threshold at this time, but the other four remained visible for a long time after the reaction time. The other subjects reacted later, so the change in target velocity was larger by the time they reacted. We thus confirm the conclusion of Port et al. (1997) that acceleration is not used in this kind of interception tasks.

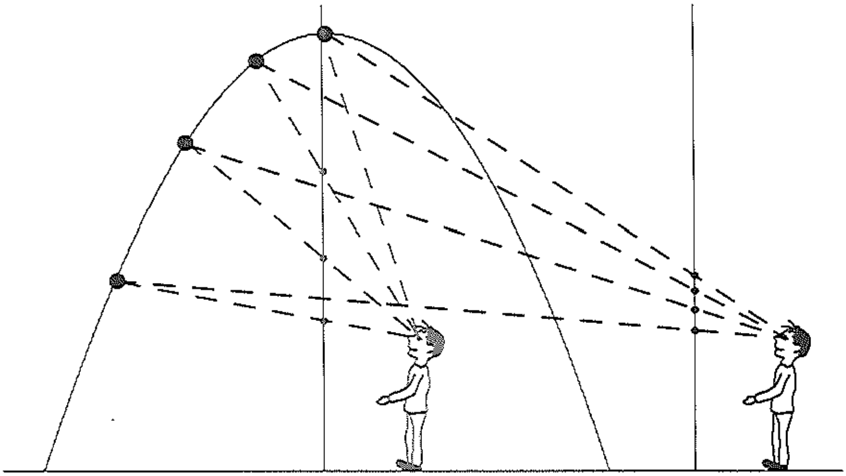

Figure 4-5. Schematic illustration of the acceleration cue for catching fly balls. Four positions of a ball following a parabolic path are indicated at equidistant time intervals. If the ball is destined to land in front of the observation point, its projection decelerates in the vertical direction (depicted as black dots on the vertical line). If the ball will land behind the initial observation point, the projection accelerates positively (gray dots on the vertical line).

Use of acceleration for catching balls

It has been proposed that acceleration is used in a very simple way for catching balls (Chapman, 1968; Babler & Dannemiller, 1993; McLeod & Dienes, 1996; Michaels & Oudejans, 1992; Lenoir et al. 1999). As depicted in Figure 4-5, the projection of a ball on a parabolic path accelerates negatively if the ball will land in front of the observation point and positively if it is destined to land behind it. In principle, all that one has to do to start moving in the right direction is to move forward if the projection decelerates and backward if it accelerates positively. This would be an elegant, simple strategy in which the catcher only has to distinguish between positive and negative acceleration.

Todd (1981) and Babler and Dannemiller (1993) both investigated the validity of this hypothesis, and reached opposite conclusions. Todd (1981) presented his subjects with a simulation of the initial part of a ball approaching on a parabolic path. The object did not change size but remained very small throughout the whole trajectory. Subjects had to indicate whether the object would land in front of or at the observer. As subjects performed poorly, Todd (1981) concluded that observers were unable to take advantage of the information contained in the acceleration. Babler and Dannemiller (1993) argued that this result might be due to the fact that the acceleration threshold of 20% change in velocity (that was found by Babler and Dannemiller themselves) was only reached in 40% of the trials. They essentially replicated Todd's experiment taking care that their threshold was reached by the time that the target disappeared. The virtual target could also land behind the observer (which was an additional choice alternative as well). Subjects correctly indicated the landing position in about 80% of the trials. Babler and Dannemiller (1993) concluded that subjects could use the image acceleration cue effectively.

A disadvantage of these studies is that simulations were used in which only the image acceleration cue was present. It is not known how the absence of other cues that are normally present influences the results. In these simulations, subjects may use the acceleration cue though they would not use it in natural situations, where there may be other cues which (when combined) provide the necessary information. One could think of changing image size, binocular information, image velocity and knowledge of the ball's size. Moreover, in the judgement tasks used by Todd (1981) and Babler and Dannemiller (1993), subjects viewed the stimulus for 0.75 to 1.25 s and responded afterwards, without any time pressure. This is substantially different from really catching a ball in which a quick detection and response are necessary.

Another approach to investigate whether subjects use acceleration to determine in which direction to move is to look at the behaviour of real (competent) ball-catchers. If they use the acceleration detection strategy described above, the response latencies should never be shorter than the time it takes for the ball to reach the detection threshold for acceleration. This will now be examined.

We used raw data from a study by Oudejans, Michaels and Bakker (1997) to see whether subjects only started running after the threshold for acceleration detection was reached. Oudejans et al. (1997) asked twelve subjects, six experts (experienced baseball outfielders) and six non-experts, to catch tennis balls. The balls were fired by a machine from behind an opaque screen. The distance between the machine and the subjects' starting position was always 18 m. The balls followed near parabolic trajectories and were fired in the subject's sagittal plane. Half of the balls were fired to varying locations between the subject and 12 m in front of him and the other half were fired to locations between the subject and 11 m behind him, in random order. Oudejans et al. (1997) determined the time that the ball was in flight, the distance it traveled, and the direction and reaction time of the foot and head movements from videotapes. The movement of one of the feet was the first detectable body movement. However, as a foot movement in a certain direction did not mean that the overall movement would be in the same direction, Oudejans et al. (1997) used the direction of initial head movement as the initial direction of locomotion. They reported that in almost half of the trials, the non-experts started to move forward though the balls were projected behind them. In the group of experts, this only occurred in one out of 180 trials. False starts in the other direction occurred in 6% of the trials in the expert group and in 4% of the non-expert group. The reaction time of the non-experts was lower than that of the experts. Oudejans et al. (1997) inferred that on many occasions, the non-experts did not respond to information about the ball's destination (they moved too early) whereas the experts did. Therefore, we only examined the trials of the experts in more detail.

To compute the moment that the velocity in the vertical direction changed by 25% for each throw we first transformed the initial velocity of the ball into an initial optical velocity (see Michaels and Oudejans, 1992). To arrive at the optical velocity that represents 25% change of the average velocity, we multiplied the initial optical velocity by 1.29 if the ball landed behind the starting position of the subject and by 0.78 if the ball landed in front. Finally we computed when this optical velocity was reached.

For each trial we compared the time at which the percentage of change in velocity in the vertical direction reached 25% with the time at which subjects started to move a foot (left of Figure 4-6). In by far the most trials subjects reacted before threshold was reached, i.e., before they could have detected whether the ball accelerated positively or negatively. Moreover there was no correlation between the reaction time and the time that the threshold was reached (R^2=0.01). However, since Oudejans et al. (1997) report that "a foot movement in a certain direction does not automatically mean that locomotion will be in the same direction", subjects may not have decided for the running direction by the time they moved a foot. Therefore, we also compared the reaction times of the head to the times that the acceleration detection threshold was reached (right of Figure 4-6). Still, in half of the trials the reaction time was before the time velocity reached the detection threshold and again, there was no correlation between the reaction time and the time that the threshold was reached (R^2=0.04). Note that if the vertical optic acceleration were used to catch balls, we would have expected the reaction time in a particular trial to be in the order of 100 ms longer than the time it takes for the threshold to be reached in that trial, because it also takes time for neural signals to result in a detectable movement.

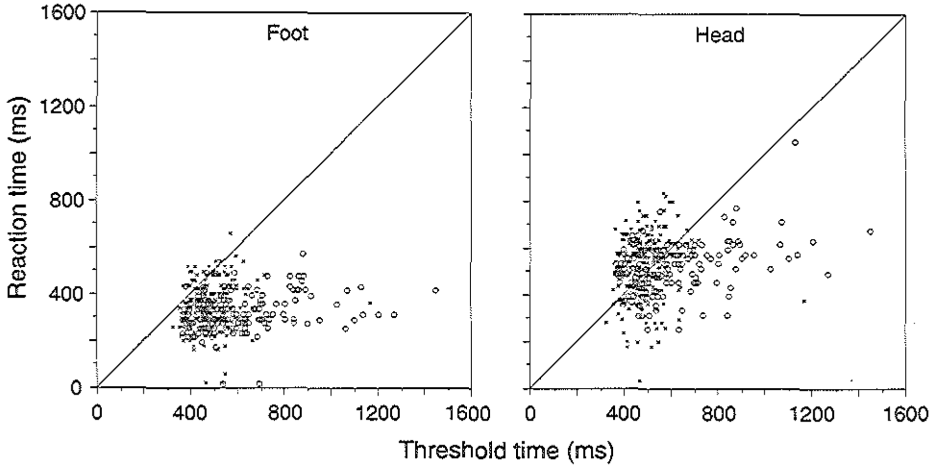

Figure 4-6. Reaction time of ball catchers in the study of Oudejans et al. (1997) of the foot (left) and of the head (right), plotted against the time that the image of the ball reached the threshold of 25% change in velocity. Trials in which the ball landed behind the starting position of the subject are represented by circles. Trials in which the ball landed in front of the starting position are represented by crosses. Most data points are below the unity line when foot reaction time is compared to the time of threshold; with head reaction time this is about half of the points. This means that in most or half of the trials subjects reacted before the threshold was reached, indicating that their action was not based on the detection of acceleration.

The acceleration detection threshold would have had to be much lower than the one we found in order to retain the hypothesis that image acceleration is used. However, our threshold is already an underestimate due to previously mentioned factors. Also, our threshold from the differential judgement task is based on a performance level of 75% correct, whereas 97% of the experts' responses were in the correct direction.

In catching balls, the motion of the image of the ball is in the vertical direction. We do not think that our threshold would have been different if we had used vertically instead of horizontally moving stimuli. Babler and Dannemiller (1993), who found a threshold about equal to ours, used vertically moving stimuli. Though Calderone and Kaiser (1989) found an interaction effect between direction of motion (horizontal or vertical) and sign of acceleration on the thresholds, the overall thresholds hardly differed between horizontally and vertically moving stimuli (if anything, the threshold for horizontally moving stimuli was slightly lower).

Thus, as subjects who are catching balls very often react before even an underestimation of the acceleration threshold is reached, we conclude that image acceleration is not used in determining in which direction to run.

A possible way to determine the correct running direction in catching balls

If it is not the sign of the acceleration of the ball's optic projection, what information could subjects use to determine the direction in which they start to run? As (expert) catchers almost always start running in the correct direction, with an average head reaction time of 526 ms, there has to be some detectable visual information that indicates very early during the ball's flight whether the ball will land ahead or behind the catcher.

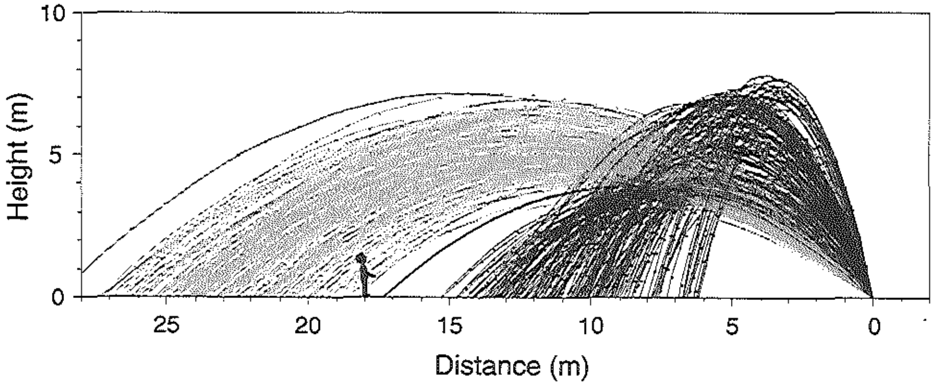

Figure 4-7. Trajectories of balls used in the experiment by Oudejans et al. (1997), as seen from the side. Gray lines represent trajectories of balls landing behind and black lines represent balls landing ahead of the catcher's initial position.

Figure 4-7 depicts the trajectories of the balls in the study of Oudejans et al. (1997) as seen from the side. It shows that the paths of balls landing behind and ahead of the catcher's initial position are initially very close and even partially overlap. This means that the initial path itself does not provide sufficient information about the ball's landing position. The information must be in the change in the ball's position over time.

The combination of horizontal and vertical speed determines the distance that a ball is going to cover. Ignoring air resistance and assuming that the ball starts moving upwards from the surface, the time T that the ball will be in flight is:

$$T = \frac{2V_v}{g} \qquad (1)$$

with g being the acceleration caused by gravity and V_v being the initial vertical speed. The horizontal distance d that the ball will cover is:

$$d = V_h T \tag{2}$$

with V_h being the speed in horizontal direction. By substituting T in equation 2 by equation 1, we find that the covered horizontal distance of a ball depends on the horizontal and vertical speed as follows:

$$d = \frac{2V_h V_v}{g} \tag{3}$$

We call the distance between the starting position of the ball and the initial position of the catcher d_{bc}. By expressing the distance that the ball will cover as a proportion of d_{bc}, we get:

$$\frac{d}{d_{bc}} = \frac{2V_h V_v}{g d_{bc}} \tag{4}$$

We call this equation the 'geometrical predicted distance'. If it is equal to 1, the ball will land at the catcher's initial position. If it is larger than 1, the ball will land behind the catcher ($d > d_{bc}$). If the geometrical predicted distance is lower than 1, the ball will land in front of the catcher ($d < d_{bc}$). We computed the geometrical predicted distance for every ball in Oudejans et al. (1997). The distribution of these values is shown in Figure 4-8A. The distribution is clearly split in two parts, one part for the balls landing in front of the catcher's initial position with values lower than 1; and one part for the balls landing behind the catcher's initial position with values higher than 1.

The question arises whether catchers are able to perceive this predicted distance in order to use it for determining whether they should run backwards or forwards. Catchers probably have implicit knowledge of g through abundant experience with gravity (McIntyre, Zago, Berthoz & Lacquaniti, 2001). It seems improbable that they have access to the exact horizontal and vertical speed of the ball. However, they may extract the predicted landing position from correlates of these variables; respectively the rate of expansion of the ball's image and the angular velocity $\dot{\theta}$. To obtain an adequate scaling of these variables, one needs a scaling factor such as ball size or distance d_{bc}. As both were constant in the experiment of Oudejans et al. (1997), this information may be acquired relatively easily. Also, there are many sources of information for the value of d_{bc} under natural conditions. A convenient expression for the (initial) horizontal speed is d_{bc} divided by tau (τ). Tau equals the ball's angular size divided by its rate of expansion and specifies the time to contact for motion at constant speed (Lee, 1976). A convenient expression for the (initial) vertical speed is d_{bc} times $\dot{\theta}$ (in rad/s). Substituting the ball's horizontal and vertical speed in equation 4 by these expressions yields a perceptual estimate of the geometrical predicted distance:

$$\frac{2d_{bc}\dot{\theta}}{g\tau} \qquad (5)$$

We call equation 5 the 'perceptual predicted distance'. Figure 4-8B shows the distribution of the values of the perceptual predicted distance for every ball shot in the experiment by Oudejans et al. (1997), computed using the change in angular position and size over the first 100 ms after the ball had been fired. At least in some trials, the information for distinguishing between balls landing ahead of and ones landing behind the catcher's initial position must be present at that time, because the shortest head reaction times are around 200 ms and time is needed for neuronal transmission and for accelerating the body. The values of the perceptual predicted distance are clearly different for balls landing behind (perceptual predicted distances >1) and in front of (perceptual predicted distances <1) the catcher's initial position. This means that the approximations of V_h and V_v used in the perceptual predicted distance are good enough to differentiate between balls landing behind and those landing in front of the catchers.

The next question is whether people can detect deviations of the predicted distance from a value of 1 well enough to be able to actually use it. We here assume that the visual system extracts the perceptual predicted distance from $\dot{\theta}$ and τ. McKee (1989) reported a 75%-correct threshold of about 6% in detecting differences between angular velocities. The mean stimulus presentation time she used was 160 ms. Regan and Hamstra (1991) found a 75%-correct discrimination threshold for tau of about 10%. They used presentation times that were generally longer than a second. The threshold may be higher for shorter presentation times when measured by using their method, in which all cues were randomized. However, there is more information available in natural situations. E.g., in the experiment of Oudejans et al. (1997), the size of the ball and the distance between the thrower and the catcher did not vary across trials. We assume that the threshold for τ is also about 10% for these conditions.

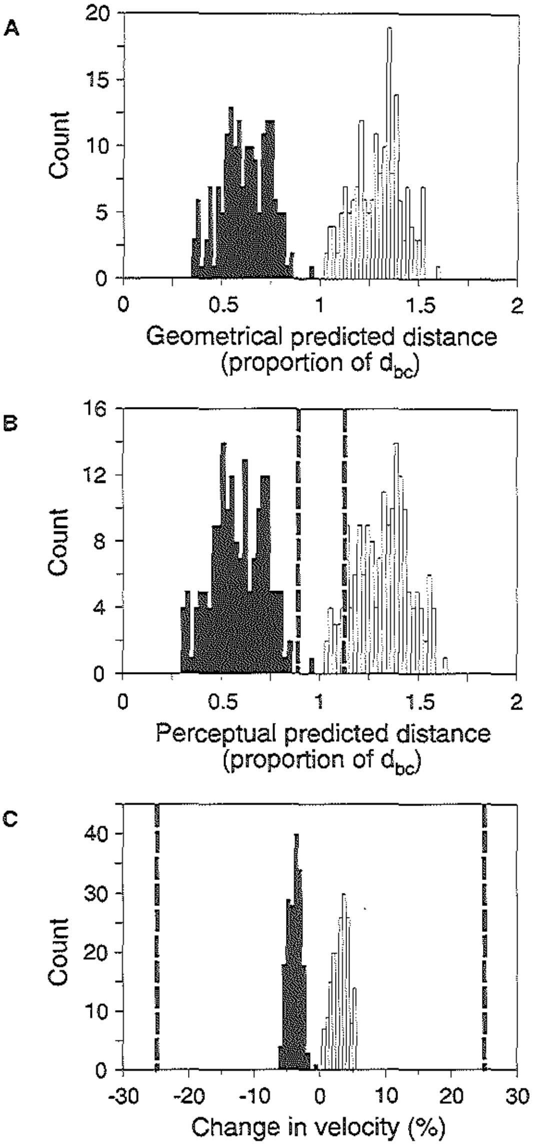

Figure 4-8. Histograms of values of the geometrical predicted distance at the start of the ball's flight (A), of values of the perceptual predicted distance calculated over the first 100 ms of the ball's flight (B), and of values of change in velocity of the ball's optic projection calculated over the first 100 ms (C). Solid bars represent balls landing ahead of the catcher's initial position. Open bars represent balls landing behind the catcher's initial position. The dotted lines in B and C represent the limits of our estimated 75%-correct thresholds for respectively perceptual predicted distance and change in velocity.

Combining the thresholds for angular velocity and tau results in a 75%-correct threshold for predicted distance of about 12%. Figure 4-8B shows that for 95% of the balls used in the experiment of Oudejans et al. (1997), the perceptual predicted distance is outside of the region between the 75%-correct thresholds (indicated by the dashed lines). This means that in most cases subjects could have distinguished the perceptual predicted distance from 1. In order to compare this result to the (rejected) hypothesis that subjects use the distinction between acceleration and deceleration for determining their running direction, we computed the change in velocity of the ball's optic projection over the first 100 ms. Figure 4-8C shows that the change in velocity indeed specifies whether a ball will land behind or ahead of the subject's initial position. However, the changes are all well within the range between the 75%-correct limits (25% change in velocity) which shows that this source of information cannot be used.

One may expect that the perceptual predicted distance only indicates the ball's landing position during a very brief period at the start of the ball's flight, because that is when the approximations of the horizontal and vertical speed are most accurate. However, calculations show that later values of $\dot{\theta}$ and τ of balls from the experiment of Oudejans et al. (1997) could still be used. Simulating balls that move higher than those of Oudejans et al. (1997) reveals that perceptual predicted distance becomes less reliable when the ball's maximal height is 15 m or higher. Whether subjects perform worse under such conditions remains to be examined. We conclude that subjects could have used perceptual predicted distance as defined in equation 5 to determine the initial running direction in the experiment of Oudejans et al. (1997).

Chapter 5

Is there evidence for coupling taus of gaps when intercepting moving targets?

Submitted as: Brouwer, A., Brenner, E., & Smeets, J. B. J. Is there evidence for coupling taus of gaps when intercepting moving targets?

Abstract

A number of studies claim to provide evidence for the tau-coupling theory of sensorimotor control. This theory proposes that various kinds of goal directed tasks are controlled by keeping the tau (time to closure) of one decreasing gap in a constant ratio to the tau of another decreasing gap. For intercepting moving targets at a specified goal zone, this leads to the hypothesis that the tau of the gap between the hand and the goal zone is maintained in a constant ratio to the tau of the gap between hand and target. Indeed Lee et al. (2001) found a linear relationship between these two decreasing taus during the last part of such a movement. We question whether this really provides evidence for the theory. We modeled smooth ballistic hand movements that led to successful interception of targets in a goal zone, and subjected such movements to Lee et al.'s (2001) analysis. We found that even though the interception movements were completely independent of the movement of the target, and therefore unrealistic, the resulting taus of decreasing gaps were related linearly. We conclude that this relationship cannot be considered as evidence for a tau-coupling theory of sensorimotor control.

Introduction

Lee introduced the optic variable tau in the context of visually controlling the braking of a car (Lee, 1976). He showed that tau, in this case the inverse of the relative rate of dilation of the retinal image of an obstacle, could inform the driver about the time to collision at the current driving speed. More generally, tau can be defined as the time it takes for a gap to close given the present speed of closing. A large number of studies has been carried out that (seem to) support the use of tau in timing a lot of different actions such as retracting wings when diving into water (gannets; Lee and Reddish, 1981), extending legs before landing on solid ground (pigeons; Lee et al. 1993), catching (Savelsbergh et al. 1991) and punching balls (Lee et al. 1983). For a critical overview of studies supporting tau see Wann (1996). Other studies have proposed alternatives for the use of tau (Smeets et al. 1996; Tresilian, 1999; Kerzel et al. 1999).

More recently Lee generalized the tau theory, proposing that various taus of closing gaps can be coupled in order to guide movements (Lee, 1998). The gaps can be defined in any dimension, such as distance, angle or force, and can even only be present internally (as an intrinsic tau-guide; Lee, 1998). This makes it possible to use the tau-coupling strategy for many different goal directed behaviors, such as bats' steering by echolocation (Lee et al. 1995), babies' sucking from a bottle (Craig and Lee, 1999), bringing food to the mouth (Lee et al. 1999) and guiding the swing in golf putting (Craig et al. 2000).

To explain the hypothesis of tau-coupling more clearly, and to illustrate the way in which evidence for the hypothesis was provided, we will describe a paper by Lee et al. (2001). In that study, subjects controlled a cursor to intercept a target just as it arrived in a particular goal zone on a computer monitor (see Figure 5-1AB). In order to succeed, all three spatial gaps in this setup (the gap between hand and goal, between target and goal and between hand and target) must close simultaneously. This means that the taus of the three closing gaps must become zero at the same time. If the taus of two gaps become zero simultaneously, it follows that the tau of the third gap reaches zero at the same time as the other two. Therefore, a successful strategy would be to keep the decreasing tau of one gap at a constant ratio to the decreasing tau of another gap. Subjects could couple the tau of the gap between hand and goal (τ_{hg}) to the tau of the gap between target and goal (τ_{tg}) (Figure 5-1A), or the tau of the gap between hand and goal to the tau of the gap between hand and target (τ_{ht}) (Figure 5-1B). Lee et al. (2001) used targets moving at a constant velocity, or with a constant acceleration or constant deceleration. They also varied the targets' movement times. For each trial, taus were computed for every 10 ms of the hand's movement. Lee et al. (2001) plotted τ_{hg} against τ_{tg} and τ_{hg} against τ_{ht}. The data points from the last part of the movement formed a straight line, indicating that at the end of the movement one tau was a fixed ratio of the other. This was particularly evident for the τ_{hg} - τ_{ht} plot. They concluded that subjects guided their hands by coupling the tau of the gap between hand and goal to that between hand and target. The other studies that support the tau-coupling theory also show that the taus of two decreasing gaps are linearly related towards the end of the movement (Lee et al. 1995, 1999; Craig and Lee 1999; Craig et al. 2000).

We wondered to what extent the data points in tau plots like those in Lee et al. (2001) necessarily converge to a straight line for any smooth movements. In their study, only successful trials were considered. Thus the taus of the gaps must by definition decrease to zero simultaneously, regardless of the strategy used. In theory the data points could reach zero along a curve, but how probable is that? In the present study we will try to answer this question by modeling a simple smooth hand movement to the kind of targets used in the experiment of Lee et al. (2001) This modeled strategy is equivalent to the 'single shot' hypothesis mentioned in Lee et al (2001): watch the target, (correctly) predict when it will reach the goal, and move the hand without adjusting it on the way. This is not the way such movements are controlled, because we know that goal directed hand movements are continuously adjusted on the basis of visual information about the target's changing position and velocity (Brenner and Smeets 1997; Brenner et al. 1998). Indeed Lee et al. (2001) found that the hand's velocity profiles differ significantly between the three types of targets (constant velocity, accelerating and decelerating). This is why they justly rejected the single shot hypothesis. However, by constructing τ_{hg} - τ_{tg} and τ_{hg} - τ_{ht} plots from single shot movements, we check whether data that are obviously not in agreement with the tau-coupling hypothesis will lead to rejection of the hypothesis. If not, i.e., if the data points in these plots also converge to straight lines, it would mean that their analysis allows data that are in conflict with the tau-coupling hypothesis to lead to the conclusion that tau-coupling is used. In that case, it would no longer be justified to consider the results of Lee et al. (2001) as support for coupling taus of gaps in goal directed behavior.

Materials and methods

Modeling

The modeled targets moved in the same way as the targets used in the experiment of Lee et al (2001). They started 12.5 cm below and 12.5 cm to the left of the goal and moved straight toward the goal (Figure 5-1AB). The target's movement time (TMT) was 0.5, 0.8, 1.1, 1.4, 1.7 or 2 s. The targets moved at a constant velocity, with a constant acceleration (with a starting velocity of 3 cm/s) or with a constant deceleration (with an ending velocity of 3 cm/s). This resulted in 18 conditions.

The modeled hand followed a minimum jerk trajectory: it followed a straight path in space and had a symmetrical velocity profile. The hand's positions over time were computed using equation 2 from Flash and Hogan (1985). Figure 2 of Lee et al. (2001) indicates that the actual movement times of the hand varied considerably. For each condition we simulated a slow movement (a movement time of TMT - 0.2 s), a movement with intermediate speed (a movement time of (TMT - 0.2 s) × 0.75) and a fast movement (a movement time of (TMT - 0.2 s) × 0.5). The value of 0.2 s represents a minimum reaction time of about 200 ms.

Lee et al. (2001) only considered the part of the hand's movement in which the velocity was higher than 10% of the maximal hand velocity in that trial. We therefore computed taus for every 10 ms from the time that the hand reached 10% of its maximal velocity until the time that the hand's velocity decreased to 10% again. In our simulation the hand reached the goal at that time, together with the target, so that the taus became zero simultaneously (as in Lee et al. (2001): see their Figure 4). The modeled hand still moved for some time (0.09 × movement time) after the target had stopped, and overshot the goal by 0.07 cm. Figure 2 of Lee et al. (2001) shows that their subjects also continued to move after the target had stopped.

Data analysis

For each trial, Lee et al. (2001) determined the duration of tau-coupling as the percentage of points in the tau plots that were fit well by a straight line. To determine the strength of tau-coupling, they computed the r^2 of the regression line through these points. They found that on average the last 45% of the data points in the τ_{hg} - τ_{tg} plot were well fit by a straight line. This was 63% in the τ_{hg} - τ_{ht} plot according to their criteria. The average r^2's were 0.983 and 0.985 respectively (note that Lee et al. (2001) left out respectively 38% and 20% of trials in which the r^2 of the regression line did not exceed 0.95).

As we cannot use their criteria in computing the duration of tau-coupling because of lack of experimental noise, we compute the r^2's of regression lines fitted through the last 45% of the data points in the τ_{hg} - τ_{tg} plots and the last 63% in the τ_{hg} - τ_{ht} plots. Although these r^2's cannot directly be compared to the ones of Lee et al. (2001), they are useful to get a rough idea and to compare the modeled outcomes between the conditions. We also judged by eye whether our tau plots also converge to straight lines.

Results

Figure 5-1CD shows tau plots from our modeled data. These plots look remarkably similar to Lee et al.'s plots (2001), as reproduced in Figure 5-1EF. The main difference is the order of the graphs of the different target velocity types. The most important issue is whether the points in our tau plots converge to straight lines. Looking at the graphs we think they do. Figure 5-2 shows the r^2 values of regressions through the final part of the points, averaged across the three target velocity types. The average r^2 for regression lines through the final 45% of data points in the τ_{hg} - τ_{tg} plots is 0.993, with little difference between short, intermediate and long movement times of the hand (Figure 5-2A). The average r^2 for regression lines through the final 63% of data points in the τ_{hg} - τ_{th} plots is 0.951. The points in the tau plots from the short movement time are closer to a straight line than the points from the intermediate and long movement times (Figure 5-2B).

Discussion

In our simulation we used hand movements that are totally independent of the movement of the target, which is unrealistic. They are also unrealistic in that the velocity profiles are symmetrical, whereas velocity profiles of real movements to static targets or targets moving at constant velocities are skewed. Still, the outcome of the analysis meets the criteria of concluding that subjects actively couple taus of gaps in order to intercept the moving object. The points in the plots representing the taus toward the end of the hand's movement can be approximated by straight lines (Figure 5-1). From the r^2 values in Figure 5-2 one could be inclined to conclude that subjects maintain τ_{hg} in a constant ratio to τ_{tg}. However, we know that this conclusion is not valid, because the data we analyzed are constructed according to a procedure that is in conflict with the use of tau-coupling. Apparently, from a constant ratio of taus one cannot conclude that tau-coupling is used. We therefore conclude that Lee et al's findings (2001) do not provide evidence for the tau-coupling hypothesis.

Lee et al. (2001) rightly dismiss the single shot hypothesis because of the different velocity profiles of the hand for the different kinds of motion of the targets (accelerating, decelerating and constant speed). However, this difference between velocity profiles may well be caused by coupling the speed of the hand to the speed of the target (Brenner et al. 1998, Brouwer et al. 2000). The fact that the velocity profiles are different only shows that the movement of the hand is adjusted during the movement. Without further experiments it is impossible to say what information is used to make these adjustments.

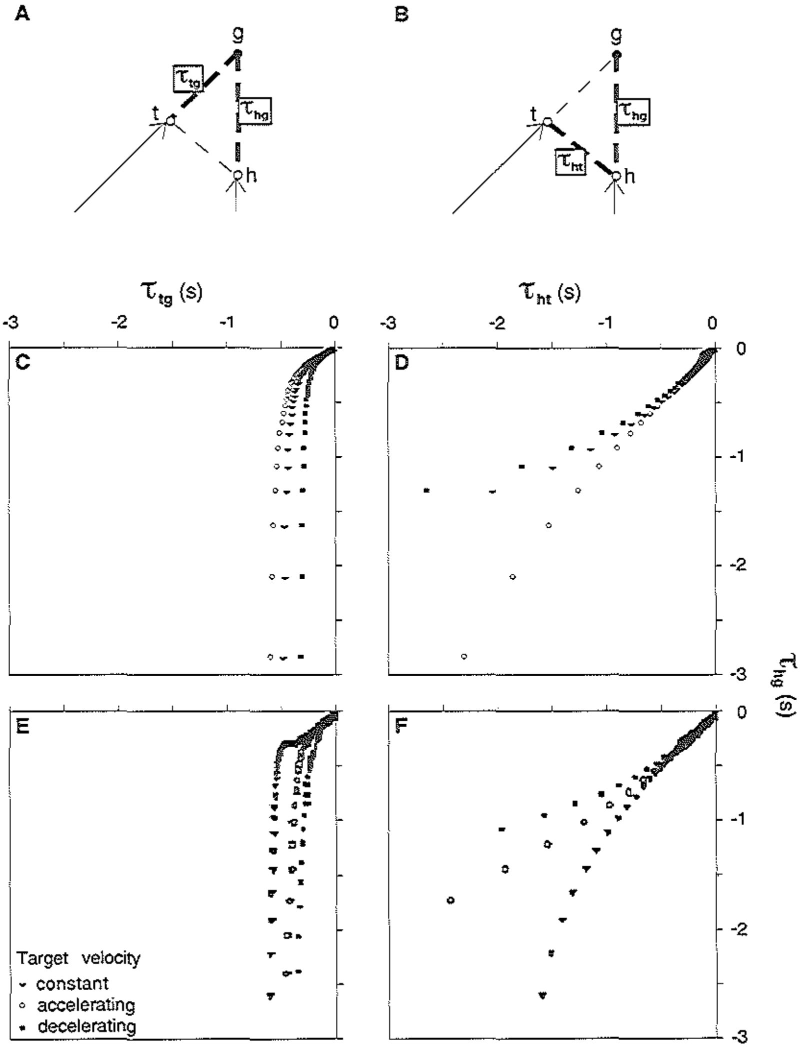

Figure 5-1. The experimental task (AB) is to move ones' hand so that a cursor (h) intercepts a target (t) as it arrives at the goal zone (g). The changing tau of the gap between hand and goal is plotted against the tau of the gap between target and goal (CE) and the tau of the gap between hand and target (DF). Plot C and D present our simulated data from the condition with a target movement time of 1.4 s and a short hand movement time of 0.6 s. Plot E and F are experimental data from Figure 4G and H of Lee et al. (2001).

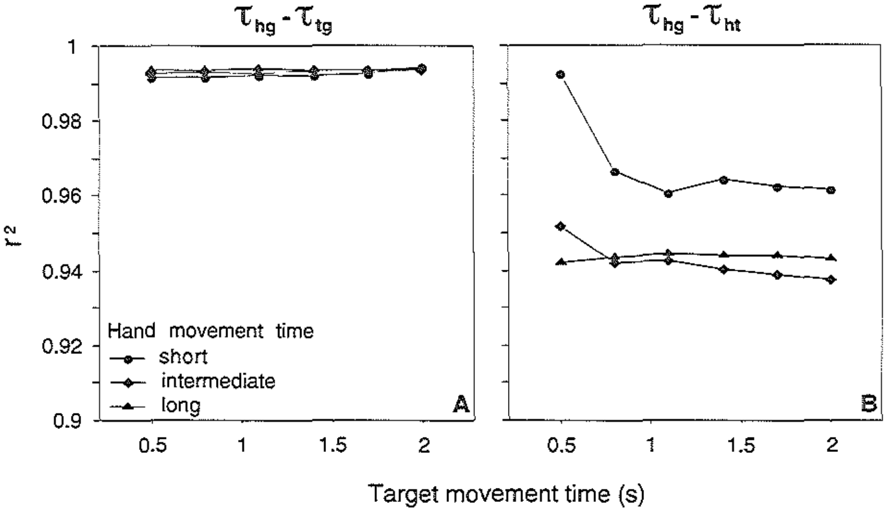

Figure 5-2. R^2 values of regressions through **A** the final 45% of the points in the τ_{hg} - τ_{tg} plots and **B** the final 63% of the points in the τ_{hg} - τ_{ht} plots, averaged over the three kinds of target velocity.

Apart from the fact that at least the study of Lee et al. (2001) does not provide evidence for the tau-coupling hypothesis, there is also a theoretical problem with tau-coupling: neuronal delays are ignored. It is not clear how it is possible to keep the tau of the gap between hand and target proportional to the tau of the gap between target and goal, because it takes time to determine the value of tau and to send the appropriate motor commands to the muscles. It would only be possible if future values of tau were predicted.

The idea of tau-coupling as presented in Lee et al. (2001) also depends on an unlikely assumption if it is to be considered as a control strategy for interception in general. It assumes that subjects who intercept a moving target determine a fixed point in space where they will contact the target. There are several indications that this is not their natural strategy. Firstly, tasks in which subjects have to intercept targets in a goal zone appear to be difficult. Lee et al. (2001) reported that subjects found their task very demanding and that performance was poor on some trials. Secondly, if the goal zone is not marked visually, there is no direct visual information regarding the tau between target and place of interception. Thirdly, experiments of Smeets and Brenner (1995) showed that hand trajectories towards static targets differ from trajectories towards targets moving at a constant velocity. If targets become invisible after varying times, the hitting position depends on the time that the target is visible (Brouwer et al., in press). These results indicate that the intended place of interception changes during the trial.

Other studies that claim to support tau-coupling (Lee et al. 1995; Craig and Lee 1999; Lee et al. 1999; Craig et al. 2000), have used essentially the same analysis as in Lee et al. (2001). A task was performed, taus of several decreasing gaps were plotted against each other, and the percentage of points lying on a straight line together with the r^2 were determined. The authors concluded that the duration and strength of tau-coupling in (one of) the tau plots were good. The present study suggests that this method is not the appropriate one to test the tau-coupling hypothesis, and therefore the conclusions of these studies should be regarded with caution.

Chapter 6

Summary and conclusions

In this thesis, we investigated the use of visual information in intercepting moving objects. We have tried to determine which sources of visual information are used in guiding different aspects of the intercepting action.

There are many interception tasks that each have their own kind of action and their own potentially useful visual information. For example, in catching balls you may have to run, whereas that is generally not necessary in hitting running spiders. The fact that the object that you want to intercept 'gets bigger' as it approaches you might be a useful source of information in catching balls. In contrast, this information is less useful in hitting spiders that run across a wall, as their movement direction is not mainly towards your eyes. We thus looked at different tasks, which implied different kinds of action and different kinds of valuable information.

An important aspect that all interception tasks have in common, is that one has to anticipate the movement of the target during one's own planning and moving. It is not possible to successfully intercept a moving target by determining the target's position and subsequently moving there, because by the time you arrive at the determined position, the target has already moved to somewhere else. It is poorly understood how this problem is solved.

In the following, chapters 2 up to 5 are summarized. After the summary I will give some general conclusions and remarks.

Chapter 2 - The dependency of hand velocity on the speed of the target

In the second chapter, we looked closer into the finding that fast targets are intercepted with quicker movements than slow targets (which we call 'speed coupling'). Speed coupling is found even if subjects are asked to always intercept the target as quickly as possible. It is also found with targets that only *seem* to move at different speeds because of background motion. Although speed coupling has been replicated often in many different tasks, it has never been explained satisfactorily why it exists.

We tested the hypothesis that speed coupling is a strategy to deal with different target speeds in intercepting moving targets. More precisely, the hypothesis claims that people account for the speed of the target by adjusting the *speed* of the hand, as they are not able to account for the speed of the target by adjusting the *path* of their hand (though as long as there is enough time, they can adjust their hand's path to the new position of the target). According to this hypothesis, speed coupling would only be necessary if the target's speed is unpredictable and if the task demands a high accuracy. We thus asked subjects to hit running virtual spiders as quickly as possible with a rod and investigated whether the speed of the hand was still coupled to the speed of the target when 1. the target's speed was predictable and 2. when the accuracy demands were low. The target's speed was made predictable by presenting the subjects with many spiders running at the same speed. The low accuracy demands were created by enlarging the tip of the rod substantially. Though according to the hypothesis, people do not need speed coupling in these conditions, we found that subjects still moved quicker to fast targets than to slow ones. Also, subjects who generally moved the hand relatively slowly, tended to have a relatively strong speed coupling. This is the opposite of what is expected by the hypothesis. The hypothesis states that if you want to arrive a certain amount earlier or later at a certain position, you must change the hand's speed more if you are a quick hitter than if you are generally slow. Thus, the hypothesis that speed coupling compensates for not adjusting the hand's path to the target's speed was rejected.

Another hypothesis to explain why people move faster to fast targets than to slow ones, is that they consider the fast targets to be more likely to get out of reach than slow targets. We carried out an additional experiment to test this hypothesis. Subjects hit spiders running from the left to the right across a screen. We found that spiders that started more to the right were not hit quicker than spiders that started more to the left, though the former should be considered more likely to get away. The hypothesis that speed coupling is caused by the impression that fast targets are more likely to get out of reach was rejected.

We proposed a new hypothesis that states that speed coupling is caused by different speed-accuracy tradeoffs for different target speeds. In hitting moving targets, you have to arrive at both the correct time and the correct position. The accuracy demands for timing are not equal for fast and slow targets; a temporal error has a larger negative effect in hitting fast targets than slow ones. There is evidence that whereas moving quickly worsens the accuracy in positioning, it improves the accuracy in timing. Thus, the optimal hand speed is higher when hitting fast targets than slow targets. This may cause speed coupling.

Chapter 3 - Is target speed used in guiding the hand's path?

From chapter 2 we learned that adjusting the hand's speed is not the (only) strategy that people use to account for different speeds of the target. There will probably be an effect of the target's speed on the hand's path. However, an effect of the target's speed on the hand's path may not be caused by the speed itself; it may also be caused by the co-varying changing position. Physically, speed is nothing more than changing position, but physiologically, these seem to be separately processed. In chapter 3, we disentangled speed and changing position by letting subjects hit spiders that became invisible after 150, 250 or 350 ms, which was always before the subject's hitting rod reached the screen. We investigated whether they use the target's speed to determine their hand's path, or more specifically, whether they use it to guide their hand to the place of interception. As an alternative to using the target's speed, subjects could only use the target's position and a certain default speed (which is the speed at which subjects assume the target to be moving; for instance the average speed of the previous targets). If subjects use the target's speed and the spider becomes invisible, they should still be able to hit approximately at the correct position. If subjects only use position and a default speed, they can use updated position information until the spider disappears. From that point on they will assume that the invisible spider runs at the default speed and hit accordingly.

From the first experiment in chapter 3, it appeared that there was an effect of the target's speed: subjects hit further ahead of the disappearing point when the spider ran faster. However, they did not hit as much ahead as they would have if they had fully used the target's speed. The results were something in between what was expected by the two hypotheses. The longer the spiders were visible, the more the target speed seemed to be used. A quantitative comparison between the actual distances that subjects hit ahead of the disappearing point and distances predicted by the hypotheses (whereby we defined the default speed as the average speed) did not favor one hypothesis significantly over the other.

We proposed two new hypotheses that incorporate the notion that both a default speed and the actual speed have an effect on the place of interception. The first is called the *extrapolation hypothesis*. According to this hypothesis, the effect of the target's speed is caused by a speed-related misperception of the target's position. It has been suggested in the literature that when a target is pursued, it is perceived a certain time ahead in the direction in which the eyes move (the extrapolation time). This means that fast targets are perceived further ahead than slow ones. In the case of hitting spiders that become invisible, the effect of the mislocalization is equivalent to using the target's speed during the extrapolation time after the spider became invisible, and using the default speed during the remaining time (until the screen is hit). Thus, the extrapolation hypothesis states that a spider hitter does not use the target's speed directly, but that she or he still accounts for the target's speed in guiding the hand by using the misperceived position of the target (which implicitly conveys information about the target's speed). The second hypothesis is the *hypothesis of progressive use of speed*. According to this hypothesis, the used speed changes from the default speed into the actual speed at some time during the presentation. When a target is visible briefly, the subject is not able to perceive the actual speed correctly and he or she will use a speed that lies between the default and the actual speed.

We created models of each hypothesis to predict the distances that the spiders ran during the time between disappearance and arrival at the screen. Each model had one fitted parameter; the extrapolation time for the model of the extrapolation hypothesis, and the time at which the use of default speed changes into the actual speed for the model of the hypothesis of progressive use of speed. The outcomes were compared to the distances subjects actually hit ahead of the disappearing point. The models appeared to be equally good.

The results of the first experiment in chapter 3 did not allow us to distinguish between the two new hypotheses. The extrapolation hypothesis considers the time between disappearance of the spider and the rod's arrival at the screen (the time that the spider is *invisible*) as crucial. If the spider is invisible for a short time, subjects make use of the target's speed relatively long; if the spider is invisible for a long time, the default speed will primarily be used. In contrast, the hypothesis of progressive use of speed considers the time that the spider is *visible* as the determining factor; the longer the spider is visible, the more the target's speed is used. In the first experiment, spiders that were visible long were always invisible shortly and vice versa, so we cannot tell which factor is the determining one: are spiders that are long visible hit better because they are long visible or because they are shortly invisible?

In the second experiment subjects were only allowed to start hitting after they heard a tone. In this way, we could present spiders that were visible for a short or a long time, but with equal times between disappearance and the rod's arrival at the screen. As predicted by the extrapolation hypothesis, both types of spiders were hit equally well. The hypothesis of progressive use of speed was wrong in predicting a better performance when spiders were visible for a long time. We also presented spiders that were visible long enough to use the actual speed, but one type of spider disappeared whereas the other type did not. The extrapolation hypothesis predicted correctly that the latter were hit better, whereas the hypothesis of progressive use of speed was wrong in predicting no difference. However, the results were not very clear. Also, the quantitative model of the extrapolation hypothesis did not predict the results of the second experiment better than the model of the hypothesis of progressive use of speed.

A third experiment was carried out to test in another way whether the target's speed itself is used in guiding the hand to the place of interception. Again subjects hit spiders that became invisible, but now the background across which the spiders ran could move. If the background moves against the running direction of the spiders, they appear to move faster, whereas they appear to move slower if the background moves in the same direction as the spiders. If the target's speed is used, subjects should hit further ahead of the disappearing point when the spider seems to move fast than when it seems to move slow. This is not what we observed.

From the experiments described in chapter 3 we conclude that, although the target's speed influences the place of interception, subjects do not use perceived target speed in guiding the hand to this place. The effect of the target's speed may result from using a speed-related misperception of the target's position.

Chapter 4 - Can acceleration be used in interception?

Chapter 4 deals with the question whether it is possible to use information about acceleration in intercepting moving targets.

Most interception tasks require quick reactions. Thus, if acceleration is to be used in interception, it must be detected quickly. Acceleration detection thresholds reported in the literature are based on experiments that used long presented stimuli. It may not be just to use these thresholds in stating something about the use of acceleration in interception, like Port, Lee, Dassonville and Georgopoulos (1997) have done. They let subjects intercept accelerating targets on a computer monitor with a cursor controlled by a computer mouse. Port et al. argued that the accelerations of the targets were detectable but that subjects did not use this information. However, the acceleration detection threshold may be higher than the ones reported in the literature when measured with shortly presented stimuli. If this is so, subjects in the experiment of Port et al. may not have used acceleration only because they were unable to detect it. We therefore measured how well people can detect acceleration when stimuli are presented shortly.

Subjects carried out two tasks, in which both the stimulus' presentation time and mean velocity were varied. In the differential judgement task, we presented two moving dots successively; one dot accelerated, the other dot decelerated. The subject's task was to indicate which dot had accelerated. In the absolute judgement task, subjects used a computer mouse to adjust the motion of an initially accelerating or decelerating dot in such a way that it appeared to move at a constant speed. This task has the advantage that it could reveal possible biases in what subjects perceive as a constant speed. We found a significant deviation of constant speed in only one out of 9 conditions. The results from the differential judgement task indicated that most subjects could detect acceleration even if the presentation time was only 300 ms. However, they did not perceive acceleration (i.e. the rate of change of velocity) itself, they rather compared velocities between the beginning and the end of the stimulus presentation and detected in this way whether the dot had accelerated or decelerated. This was evidenced from the fact that for both tasks, the detection thresholds depended strongly on the presentation time and mean velocity when expressed as accelerations (they decreased with presentation time and increased with mean velocity), whereas the detection thresholds were independent or less dependent on presentation time and mean velocity when expressed as percentage change in velocity. This has been found before. A change of velocity of 25% was needed to detect acceleration with reasonable confidence, which is low compared to thresholds reported in the literature.

Herewith we confirmed the claim of Port et al. (1997) that the accelerations of their stimuli were detectable; the presented accelerations were higher than the detection threshold measured during short presentation times. Thus acceleration seems indeed not to be used in this kind of interception task.

For another interception task, it has been claimed that acceleration is used in a different, simple way. This task is catching balls that are approaching following a parabolic path. The relation between the acceleration of the target and the optic angular acceleration is rather complex in this case. Still, detecting angular acceleration could be useful because it conveys information about the ball's landing position: the projection of the ball on a plane accelerates if it will land behind you, whereas it decelerates if it will land in front of you (see Figure 4-5). Thus, catchers only need to differentiate between acceleration and deceleration in order to determine whether they should start running backwards or forwards. If this strategy is indeed used, catchers can only start running after they detected whether the projection decelerates or accelerates. We determined whether this is true by analyzing data of Oudejans, Michaels and Bakker (1997) who let subjects catch balls. Oudejans et al. registered the subjects' foot and head reaction times, as well as the time that the ball was in flight and the distance it traveled. Thus, for each trial we could compare the reaction time to the time that the ball's image reached the threshold of 25% velocity change. It appeared that in by far most trials subjects moved their foot before they could have detected the difference between acceleration and deceleration. The movement of the foot was the first measurable movement of the subject. Maybe subjects had not yet chosen a running direction by that time. We thus compared the head reaction times to the times that the threshold was reached as well. Again, in many trials the reaction time was shorter than the time of threshold. Note that our threshold of 25% velocity change is a low estimate and that it is based on a performance level of 75% correct, whereas 97% of the catcher's responses were correct. Also, after detecting whether the ball's projection accelerated or decelerated, catchers need time to initiate their movements. According to the hypothesis that catchers use acceleration, the time that 25% velocity change is reached should be positively correlated with reaction time, regardless of the value of the acceleration detection threshold. This was not the case. We concluded that catchers do not use acceleration of the ball's projection in determining the running direction.

We proposed an alternative way to determine the running direction. The distance that a flying ball will cover, expressed as the proportion of the distance between the starting point of the ball and the initial position of the catcher, can be computed from 1. the distance between the starting point of the ball and the initial position of the catcher, 2. gravitational acceleration, 3. the ball's initial vertical speed, and 4. its horizontal speed. This 'geometrical predicted distance' is lower then 1 if the ball lands in front of the catcher and higher than 1 if it lands behind. Do catchers have access to these four sources of information? We assumed that the distance between the starting point of the ball and the initial position of the catcher can be estimated accurately, at least in the experiment of Oudejans et al., in which this distance did not vary. We also assumed that people have implicit knowledge of gravitational acceleration. Catchers do not directly have access to the ball's initial vertical speed and the ball's horizontal speed. However, these can be estimated by using angular velocity and the rate of expansion of the ball's image respectively. We substituted the horizontal and vertical velocity in the formula of the geometrical predicted distance by these estimates, and computed the 'perceptual predicted distance' for every ball in the experiment of Oudejans et al. It could distinguish between balls landing ahead and behind the subjects. If published detection thresholds of angular velocity and rate of expansion are taken into account, subjects should have been able to detect the difference between balls landing ahead and behind them 100 ms after the start of the ball's flight for 95% of the balls in the experiment of Oudejans et al. After 100 ms there is not a single ball of which the projection reached 25% change in velocity. We concluded that subjects in the experiment of Oudejans et al. may have used perceptual predicted distance to determine their initial running direction.

Chapter 5 - Is there evidence for coupling taus of gaps when intercepting moving targets?

In chapter 5, we tested the method that is used by Lee and his colleagues to provide evidence for the tau coupling theory of sensorimotor control. This theory is based on the optic variable tau. Tau can be defined as the time it takes for a gap to close at the current closure speed. According to the tau coupling theory, people (and animals) couple the tau of one closing gap to the tau of another closing gap in order to perform goal directed behavior. 'Coupling' two taus means keeping two taus in constant ratio, so that they become zero simultaneously. A 'gap' is the difference between the current state and the goal state. It can be defined in any dimension such as distance, angle and force. Various types of behavior can be and has been described in terms of tau coupling.

We concentrated on a study by Lee, Georgopoulos, Clark, Craig and Port (2001) in which subjects controlled a cursor to intercept a target just as it arrived in a particular goal zone on a computer monitor. In this setup, three decreasing gaps can be discerned: hand-goal, target-goal and hand-target (Figure 5-1A and 5-1B). All three gaps close at the same time if the subject succeeds. Lee et al. hypothesized that subjects couple the tau of the decreasing gap between hand and goal (τ_{hg}) either to the tau of the decreasing gap between target and goal (τ_{tg}) or to the tau of the decreasing gap between hand and target (τ_{ht}). Targets with different movement times were presented. They accelerated, decelerated or moved at a constant speed. For each trial in which the target was successfully intercepted, taus were computed for every 10 ms of the movement. Subsequently, Lee et al. plotted τ_{hg} against τ_{tg} and τ_{hg} against τ_{ht}. At the end of the movement, as the tau values converged to zero, they formed a straight line, indicating a fixed ratio between taus. This was particularly so for the

τ_{hg} - τ_{ht} plot. Lee et al. concluded that subjects coupled τ_{hg} to τ_{ht} in order to intercept the targets. They also noted that the hand velocity profiles depended on the target motion type (accelerating, decelerating or constant speed). From this they concluded that the subjects did not move their hands in single, smooth (ballistic) movements to the goal zone after having predicted (correctly) when the target would arrive at the goal zone.

We wondered to what extent any successful smooth movement would lead to tau plots with data points converging to a straight line. We modeled ballistic hand movements to the same targets as those used by Lee et al. If the method of Lee et al. is valid and if we apply it to the simulated data, the tau-coupling hypothesis should be rejected, because the simulated data are not in agreement with tau coupling.

In contrast, it appeared that in tau plots from our simulated data, the data points also converge to straight lines. Our plots looked very similar to the tau-plots from Lee et al. Apparently, a constant tau ratio at the end of a movement does not indicate that tau coupling is used. We concluded that Lee et al. (2001) did not provide evidence for tau coupling. Other studies in which it is claimed that evidence for tau coupling is found used a similar method as Lee et al. (2001). Thus, it is doubtful whether these studies really provide evidence for the use of tau coupling. In chapter 5 we also describe some problems of the general idea of tau coupling (as a strategy for interception). One of these is that neuronal delays are ignored. Without predicting future values of tau it is not possible to keep the one tau proportional to the other because time is needed to detect the tau values and to move the body. Also, for many tasks it is not clear how tau is actually perceived.

General conclusions and remarks

Not all visual information is used

Visual information that is potentially useful and available for an ideal observer, is not always used for (certain aspects of) intercepting moving objects. In some cases this is not surprising, as people are not sensitive to that information. In other cases they are not sensitive enough. Finally, people can detect certain visual information very well, but they just do not use it in particular aspects of the action. I will give examples from this thesis for each of these three categories.

In chapter 5 we tested the method that is used to provide evidence for the tau coupling theory (Lee, 1998), and found that it was invalid. We did not directly test whether people are sensitive to taus of gaps and whether they use it in controlling their movements. Nevertheless, I think that, at least in tasks like hitting spiders, it is unlikely that people can detect the taus of gaps that would be relevant. In hitting spiders (as well as in most other interception tasks) the position where the target is intercepted is not marked visually. It is thus hard to imagine how, for instance, the tau of the gap between hand and interception position can be detected. If this information cannot be detected, it cannot be used. In chapter 4 we showed that people cannot perceive the rate of change of velocity (which has also been found by Schmerler, 1976; Gottsdanker, Frick & Lockard, 1961; Calderone & Kaiser, 1989). Thus, they will (probably) not be able to use the rate of change of velocity in intercepting moving objects in the sense of predicting exactly where an accelerating object will be after a certain amount of time.

In chapter 4 we showed that, though people cannot perceive acceleration, they are able to detect it by comparing velocities. However, they appeared not to be sensitive enough for changes in velocity to use this in determining the running direction for catching balls. In principle, all that a catcher has to do in choosing the correct running direction, is to determine whether the ball's projection accelerates (in that case he or she has to run backwards) or decelerates (then he or she has to run forwards). Our results indicated that catchers in a study by Oudejans, Michaels and Bakker (1997) must have used another source of information for which they were more sensitive, because they started to move in the correct direction before the change in velocity was large enough to be detected.

We found two sources of information which people should have been able to detect by the time that they carried out a certain interceptive action, but which they still did not use in (a particular aspect of) the action. The dependency of the hand's speed on the speed of the spider (chapter 2) showed that the speed of running spiders was detectable. However, the experiments in chapter 3 indicated that the spider's speed was not used in guiding the hand's path. In the task of Port, Lee, Dassonville and Georgopoulos (1997) subjects had to intercept accelerating or decelerating targets on a screen at a specified goal zone. We showed that the change of velocity of the targets was large enough to be detected (chapter 4). Thus, in principle subjects could have compensated for the acceleration or deceleration of the target by adjusting the moment they arrived at the goal zone. Still, they arrived too early at the goal zone when the target decelerated and too late when it accelerated. This indicates that subjects did not use the distinction between acceleration and deceleration (fully) in this task.

Distinguishing between timing and positioning

In intercepting moving objects, the *combined* timing (reaction time and movement time) and positioning (e.g. the hand's path) determine whether the target is intercepted or not. People can intercept the same target using different intercepting positions if the timing is properly attuned to the positioning, and targets can be intercepted with different reaction- and movement times if the positioning is properly adjusted. One may conclude from this that temporal and spatial aspects of the action should not be investigated as separate entities. However, I think that it is important to (also) look at temporal and spatial aspects separately.

Firstly, this is suggested by our finding that the target's speed is used to control the hand's speed (chapter 2) whereas it is not used in guiding the hand's path (chapter 3). Secondly, we described how speed-accuracy tradeoffs may be different for fast movements and slow movements; moving fast will probably increase the timing accuracy whereas it will decrease the accuracy in positioning. This differential effect of movement speed on timing and positioning was used in chapter 2 to explain the advantage of moving quicker to fast targets than to slow ones (this explanation is also supported by Tresilian and Lonergan, 2002, and Brenner, de Lussanet and Smeets, in press).

Predicting future target positions?

As stated before in this thesis, a central problem of intercepting moving objects is that catchers or hitters have to take into account that the target moves whilst they themselves are planning and moving. It seems necessary for catchers or hitters to 'predict' the moving target's future positions over time. However, some authors (supporting the ecological approach) consider this 'predicting' implausible. They doubt whether the information available to the catcher is accurate enough (Peper, Bootsma, Mestre, & Bakker, 1994; McLeod & Dienes, 1996) or they think that predicting is computationally cumbersome and prone to error (Montagne, Laurent, Durey, & Bootsma, 1999). A few interception models that can do without predicting future positions have been proposed (Chapman, 1968; Lee, 1998; McBeath, Shaffer & Kaiser, 1995; Peper et al., 1994; Zaal, Bootsma, & van Wieringen, 1999). According to these continuous control models, subjects establish and maintain a certain relationship between the target and the interception movement, until interception 'automatically' takes place. The experimental results that these models expect are often contrasted to results that are expected if catchers or hitters could perfectly predict the future interception position right from the start of the target's movement. For example, it is suggested that if subjects predict the interception position, movements to targets that are intercepted at the same position would be exactly equal, independent of the target's movement direction or speed (provided that subjects start the interceptive action at the equal positions; Peper et al., 1994; Montagne et al., 1999, Lee et al. 2001). Another example is the suggestion that ball catchers who predict the landing position of the ball would run immediately and quickly to the correct position (McLeod & Dienes, 1996; Oudejans, Michaels & Bakker, 1997).

In this thesis, we looked more closely to two of the models that describe interception without predicting future target positions. These are running in such a way that the projection of a ball moves at a constant velocity (chapter 4) and tau coupling[4] (chapter 5). The former model was rejected and the method that seemed to provide evidence for the latter model proved to be invalid. Other models are complex and difficult to test (Peper et al., 1994; Zaal, Bootsma & van Wieringen, 1999).

Besides the fact that we failed to provide support for two of the continuous control models, it is evident that coupling the movement to visual information cannot be the only essential thing in interception. This is demonstrated by the fact that you are able to hit spiders, although there is temporarily no visual information about them (chapter 3) and by the fact that information about previous targets can be taken into account (Button, Davids, Bennett & Savelsbergh, 2002; de Lussanet, Smeets & Brenner, 2001). It is also evident that if the interception position is predicted, this will not be a perfect prediction, available right from the start. A prediction that is improved continuously during the intercepting movement will be a more plausible kind of predicting. Viewing it this way, predicting does not need to be very complex because it does not have to be correct right at the start of the target's movement. Also, in chapter 3, we gave an example of something that could be called a prediction that arises automatically; misperceiving a moving target a fixed time into its movement direction. In sum, I think it is not necessary and not justified to abandon the idea of prediction in intercepting a priori.

Multiple sources of information; differences between situations and subjects

For the research described in this thesis, we were interested in the *general* behavior of healthy subjects. We approached the question of the use of visual information in interception as if for each task, there are one or two distinct sources of information that are or are not used by every subject to guide (a certain aspect of) the action. We assumed that in tasks like hitting a spider, which takes place within a second and in which there are probably not so many different sources of visual information present, people behave rather similarly.

In general it holds that the more complicated a task is and the more sources of information are available, the stronger the effect of strategy, learning and differences between subjects will be. Several studies indicate that people use multiple sources of visual information in guiding their action (Michaels, Zeinstra & Oudejans, 2001; Rushton & Wann, 1999; van der Kamp, Savelsbergh & Smeets, 1997; Michaels & Oudejans, 1992). Which sources are (mostly) used, will depend on the situation and on the experience, knowledge and general capabilities of the subject. This does not imply that behavior in complex tasks cannot be investigated. However, an investigator whose task may be 'complex' should keep

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[4] Actually, if the interception position is not visually marked, some predicting is assumed in intercepting moving objects when the tau of the gap between the intercepting effector and the interception position is coupled to another tau of a gap; namely, the interception position has to be some future position of the target.

in mind that factors such as strategy and learning may play a role, and always check whether the data looks similar between subjects and over time before basing a conclusion on the average data.

An example of the use of multiple sources of information across different situations is catching balls with or without one patched eye. Subjects may use binocular vision (when the ball is close), but they definitely do not always exclusively rely on this source of information as is evidenced by the fact that people with one patched eye can catch balls (van der Kamp, Savelsbergh & Smeets, 1997). As mentioned in the introduction, even catchers who view with two eyes do not always use binocular cues when the ball's trajectory is very predictable (Servos & Goodale, 1998) and when more effective cues are available (Rushton & Wann, 1999).

A study by Michaels and Oudejans (1992) illustrates the use of multiple sources of information across different subjects. Michaels and Oudejans simulated balls on a computer monitor and let subjects judge whether the ball would land ahead or behind them. The results suggested that different subjects preferred different optic variables in carrying out this task. Although the most effective strategy would have been judging 'ahead' if the simulated projection of the ball decelerated and 'behind' if it accelerated, many subjects appeared to use its height or peak velocity. Probably, if subjects got feedback and if these variables did not correlate with the landing position (as they did in the experiment of Michaels and Oudejans), subjects would have used these variables to a lesser extent.

Differences between subjects are not stressed in this thesis but they have been noted. In chapter 2 it appeared that some subjects chose to hit spiders quickly with little speed coupling and that others chose to hit more slowly and use more speed coupling. There were also differences in how well people could detect acceleration (chapter 4); three out of ten subjects did not reach the performance that we required for analyzing the data. In chapter 4 we also mentioned the difference between expert and non-expert ball catchers that Oudejans, Michaels and Bakker (1997) noted. Experts were far better in choosing the correct running direction and started running later than non-experts. This indicates that in this case, people have to learn what the most relevant sources of visual information are and how to use them properly. McLeod (1987) argues that in batting a cricket ball, the major difference between experts and non-experts lies in carrying out the motor task. However, also in this task experts seem to be more capable in using visual information properly to predict where and when the ball will reach them than non-experts as reflected in differential oculo-motor behavior (Land & McLeod, 2000).

A general description of how visual information may be used in interception

As already mentioned, the kind of visual information that is used in intercepting moving objects and the kind of action that must be regulated depend very much on the task. Further, there are differences in experience and used strategy between subjects and situations. For these reasons, it is impossible to create a simple theory that precisely describes what visual information is used in what way to intercept moving objects in every interception task. However, I can summarize what has been stated in this thesis before and provide a general idea of how it might work.

An exact prediction of the time and place of interception, available right from the start of the target's movement, will be impossible because of limitations imposed by visual detection thresholds and the capacity of the brain to compute things 'exactly' (especially when considering the time limits). It is also improbable considering our finding that not all information is used that would have been useful in predicting the exact future position of the target. An alternative could be that in intercepting moving targets, one roughly estimates the time and the place of interception and continuously improves this estimate by using new, updated information of the target and the interception effector. Because of this updating, unexpected movements of the target could be taken into account relatively easily. Implicit knowledge gained by experience (for instance, about gravitational acceleration or the reliability of the different sources of information) will help to make good estimates. Different sources of information may be used for regulating different aspects of the interceptive action. In hitting a fast spider, the target's speed may cause the hitter to determine that it must be hit fast. The spider's (misperceived) position may be used to determine the appropriate hitting position.

Future experiments

Clearly, many questions about the use of visual information in intercepting moving objects remain unanswered. With regard to the research described in this thesis, it would be particularly interesting to test the validity of the new hypotheses proposed in chapter 2, chapter 3 and chapter 4.

In chapter 2 we suggested that people move faster to fast targets than to slow ones because accurate timing is relatively more important for fast targets and timing accuracy increases by moving fast. They do this at the cost of a decreased accuracy in positioning. This hypothesis can be tested in a setup in which the importance of accurate timing and accurate positioning can be easily and systematically varied. For example, one could present subjects with a target that is alternately 'on' and 'off' for fixed time intervals. The subjects are asked to look at the target for as long as they like and then hit it when it is on. The timing demands can be varied by changing the duration that the target is on and the positioning demands can be varied by changing the size of the target. The hypothesis predicts that equally sized targets are hit with a faster movement when the target is on shortly than when it is on for a longer time interval. When the target's size is increased, the movement will even be faster (up to a certain limit).

In chapter 3 we proposed that the effect of the target's speed is mediated by a speed-related misperception of the target's position. According to Brenner et al. (2001), this misperception is caused by combining incoming retinal information with outgoing oculomotor commands. In other words, the target is perceived at the position where you just commanded your eyes to look. If this is so, there should be a relation between the hitting position and the eye movements. For instance, when subjects do not properly pursue the target, the effect of the target's velocity on the hitting position should be less than when they pursue correctly. It would thus be interesting to measure the subject's eye movements during hitting (disappearing) spiders.

Chapter 4 ends with the proposal that ball catchers may use the perceptual predicted distance in determining whether they should run backwards or forwards. We know that the perceptual predicted distance of balls that are shot higher than 15 m start to deviate rather strongly from the actual distance they will cover. To explore the use of perceptual predicted distance in determining the running direction we could systematically determinate what kind of balls yield perceptual predicted distances that clearly deviate from the actual distance, and subsequently investigate whether catchers indeed experience difficulties in determining the correct running direction with these balls. It may be possible to let a ball machine shoot balls whose perceptual predicted distances clearly indicate that the catcher should run backwards, whereas the ball will actually land ahead of the catcher's initial position (and vice versa). At least we could rank balls according to the difficulty that catchers should experience in choosing the correct running direction, and compare this with the experienced catcher's performance. Additionally, we may present experienced catchers balls in a virtual world (such as the CAVE, Zaal & Michaels, 2001) and manipulate the perceptual predicted distance by manipulating the relevant parameters. If experienced catchers indeed use this variable, we should be able to predict in which trials they will expect the ball to land ahead of them and in which trials they will expect the ball to land behind.

A topic of research that we left aside though it would have fit in the scope of this thesis, is the use of the target's movement direction in hitting targets moving across a frontal plane. As is the case with speed and changing position, movement direction and changing position also seem to be separately processed, though physically they are inseparable. This is demonstrated by Smeets and Brenner (1995b). They presented their subjects with targets that moved across a background that was moving perpendicularly to the target's movement direction. Whereas the motion of the background clearly affected subjects' estimates of the target's direction, the estimated position was not affected. It would be interesting to see whether, analogous to our findings in chapter 3, subjects only use the perceived position of the target and not the perceived movement direction in determining the hitting position in hitting disappearing targets.

Hoofdstuk 6

Samenvatting en conclusies

In dit proefschrift is het gebruik van visuele informatie in het onderscheppen van bewegende voorwerpen onderzocht. We hebben geprobeerd te bepalen welke informatie wordt gebruikt in het sturen van de verschillende aspecten van de beweging die gemaakt wordt om het voorwerp te onderscheppen.

Er zijn veel verschillende taken waarin bewegende voorwerpen worden onderschept. Elke taak brengt zijn eigen benodigde actie en zijn eigen potentieel nuttige visuele informatie met zich mee. Tijdens het vangen van ballen kan het bijvoorbeeld nodig zijn om te rennen, terwijl dat meestal niet nodig is bij het slaan van bewegende spinnen. Het feit dat een voorwerp dat je wilt onderscheppen 'groter wordt' naarmate het dichterbij komt, kan een nuttige bron van informatie zijn voor het vangen van ballen. Deze informatie zal echter minder nuttig zijn voor het slaan van een spin die over een muur rent, aangezien de richting waarin hij beweegt niet hoofdzakelijk richting je ogen is (in tegenstelling tot de bal). We hebben dus verschillende taken bekeken met de bijbehorende verscheidenheid aan aspecten van beweging en visuele informatie.

Een belangrijke overeenkomst tussen alle taken waarin bewegende voorwerpen worden onderschept, is dat je er rekening mee moet houden dat een bewegend doel blijft bewegen gedurende de tijd dat jij je eigen beweging plant en uitvoert. Om met succes een bewegend doel te pakken te krijgen, is het dus niet mogelijk om de positie van het doel te bepalen en daar vervolgens heen te bewegen, aangezien het doel alweer van positie is veranderd tegen de tijd dat jij daar aankomt. Er is nog maar weinig bekend over hoe dit probleem wordt oplost.

Hieronder volgt een samenvatting van hoofdstuk 2 tot en met 5. Na de samenvatting volgen enkele algemene conclusies en opmerkingen.

Hoofdstuk 2 - De invloed van doelsnelheid op handsnelheid

In hoofdstuk 2 wordt ingegaan op het verschijnsel dat een snel doel met een snellere beweging wordt onderschept dan een langzaam doel ('snelheidskoppeling'), zelfs als proefpersonen de opdracht krijgen altijd zo snel mogelijk te bewegen. Men vindt het verschijnsel ook als de doelen alleen met verschillende snelheden *lijken* te bewegen doordat de achtergrond beweegt. Ondanks het algemene voorkomen van snelheidskoppeling, is er nooit een goede verklaring gegeven voor het bestaan ervan.

Wij hebben de hypothese getest dat snelheidskoppeling een strategie is om rekening te houden met verschillende doelsnelheden tijdens het onderscheppen van bewegende doelen. De hypothese stelt dat mensen rekening houden met de doelsnelheid door de hand*snelheid* aan te passen, aangezien zij niet in staat zijn om voor dit doel het hand*pad* aan te passen (hoewel ze, zolang er nog genoeg tijd is, het handpad wel aan de nieuwe positie van het doel kunnen aanpassen). Volgens deze hypothese is snelheidskoppeling alleen nodig als de doelsnelheid onvoorspelbaar is en als een hoge nauwkeurigheid is vereist. Wij vroegen onze proefpersonen dus om zo snel mogelijk rennende spinnen te slaan met een stokje en onderzochten of de handsnelheid nog steeds aan de doelsnelheid was gekoppeld als 1. de doelsnelheid voorspelbaar was en 2. als de proefpersonen niet nauwkeurig hoefden te zijn. Wij maakten de doelsnelheid voorspelbaar door de proefpersonen veel spinnen te presenteren die telkens op dezelfde snelheid liepen. De lage nauwkeurigheidseisen werden gecreëerd door het sla-oppervlak van het stokje flink te vergroten. Hoewel je volgens de hypothese geen snelheidskoppeling nodig hebt onder deze omstandigheden, bleken de proefpersonen nog steeds sneller te bewegen naar snelle doelen dan naar langzame. Wij vonden ook dat proefpersonen die over het algemeen langzaam bewogen, vaak een relatief sterke snelheidskoppeling vertoonden. Dit had volgens de hypothese juist omgekeerd moeten zijn. De hypothese stelt dat als je een bepaalde tijd eerder of later aan wilt komen op een bepaalde positie, je je handsnelheid méér moet veranderen als je een snelle spinnenmepper bent dan als je over het algemeen langzaam slaat. De hypothese dat snelheidskoppeling compenseert voor het niet aanpassen van het handpad aan de doelsnelheid werd dus verworpen.

Een andere hypothese die zou kunnen verklaren waarom mensen sneller bewegen naar snelle doelen dan naar langzame, is dat zij denken dat de snelle doelen eerder buiten bereik zijn dan langzame doelen. We voerden nog een experiment uit om deze hypothese te toetsen. Proefpersonen sloegen spinnen die van links naar rechts over een scherm renden. Het bleek dat spinnen die verder naar rechts begonnen met rennen niet sneller werden geslagen dan spinnen die meer naar links begonnen, hoewel de eerste groep spinnen wel beschouwd zou moeten worden als spinnen die sneller buiten bereik zijn. De hypothese dat snelheidskoppeling wordt veroorzaakt door de indruk dat snelle spinnen sneller buiten bereik zullen zijn, werd dus verworpen.

We bedachten een nieuwe hypothese die stelt dat snelheidskoppeling wordt veroorzaakt doordat de handsnelheid de sla-nauwkeurigheid verschillend beïnvloedt bij verschillende doelsnelheden. Bij het slaan van bewegende doelen wil je op de juiste tijd én de juiste plaats aankomen. De nauwkeurigheidseisen die gesteld worden aan de timing zijn echter niet dezelfde voor snelle en langzame doelen; een fout in aankomsttijd heeft een groter negatief effect bij het slaan van een snel doel dan een langzaam doel. Er zijn aanwijzingen dat, hoewel snel bewegen tot onnauwkeurigheid in het aankomen op een bepaalde positie leidt, snel bewegen de nauwkeurigheid in timing juist verbetert. De optimale handsnelheid is dus hoger bij het slaan van snelle doelen dan bij langzame doelen. Dit zou snelheidskoppeling kunnen veroorzaken.

Hoofdstuk 3 - Wordt handsnelheid gebruikt in het sturen van het handpad?

Van hoofdstuk 2 hebben we geleerd dat mensen niet (helemaal) rekening houden met verschillende doelsnelheden door het aanpassen van de handsnelheid. De doelsnelheid zal waarschijnlijk dus toch het handpad beïnvloeden. Een effect van de doelsnelheid op het handpad hoeft echter niet te worden veroorzaakt door de snelheid zelf; het zou ook veroorzaakt kunnen worden door de co-variërende verandering in doelpositie. Natuurkundig gezien is snelheid niets anders dan veranderende positie, maar fysiologisch lijken snelheid en positie apart te worden verwerkt. In hoofdstuk 3 hebben we snelheid en veranderende positie uit elkaar gehaald door proefpersonen spinnen te laten slaan die onzichtbaar werden na 150, 250 of 350 ms; altijd vóór het stokje van de proefpersoon het scherm bereikte. We onderzochten of de proefpersonen de doelsnelheid gebruikten in het vormen van het handpad; om precies te zijn, in het bepalen van de eindpositie van het sla-stokje. In plaats van het gebruiken van de doelsnelheid zouden proefpersonen alleen gebruik kunnen maken van de doelpositie en een bepaalde default snelheid (dat is de snelheid waarop de proefpersonen aannemen dat het doel beweegt, bijvoorbeeld de gemiddelde snelheid van voorgaande doelen). Als proefpersonen de doelsnelheid gebruiken en de spin wordt onzichtbaar, dan zouden ze nog steeds ongeveer de juiste plek moeten kunnen raken. Als proefpersonen alleen de positie en een default snelheid gebruiken, dan kunnen ze gebruik maken van steeds de nieuwste doelpositie totdat de spin verdwijnt. Vanaf dat punt zouden ze aannemen dat de spin op de default snelheid rent en overeenkomstig slaan.

Uit het eerste experiment in hoofdstuk 3 kwam naar voren dat er een effect was van de doelsnelheid: proefpersonen sloegen verder voor het verdwijnpunt naarmate de spin harder liep. Ze sloegen echter niet zo ver als ze zouden hebben gedaan als ze de doelsnelheid helemaal hadden gebruikt. De resultaten lagen tussen de voorspellingen van de twee hypotheses in. De doelsnelheid leek wel meer te worden gebruikt naarmate de spin langer zichtbaar was. Een kwantitatieve vergelijking tussen de afstanden die de proefpersonen voor het verdwijnpunt sloegen en de afstanden voorspeld door de hypotheses (waarbij we de defaultsnelheid gelijk stelden aan de gemiddelde spinsnelheid) leverde geen significant betere prestatie van een van beide hypotheses op.

We bedachten twee nieuwe hypotheses die stellen dat zowel de default snelheid als de doelsnelheid de eindpositie van het stokje beïnvloeden. De eerste is de *extrapolatie-hypothese*. Volgens deze hypothese is het effect van de doelsnelheid het gevolg van een snelheidsgerelateerde fout in het waarnemen van de doelpositie. In de literatuur is gesuggereerd dat als een doel wordt gevolgd door de ogen, dit doel een bepaalde tijd verder in de richting waarin de ogen bewegen wordt waargenomen (de extrapolatietijd). Dit betekent dat snelle doelen verder naar voren worden waargenomen dan langzame doelen. In het geval van het slaan van spinnen die onzichtbaar worden, is het effect van de waarnemingsfout equivalent aan het gebruik van de doelsnelheid gedurende de extrapolatietijd vanaf het verdwijnen van de spin, en het gebruik van de default snelheid gedurende de resterende tijd totdat het scherm wordt geraakt. De extrapolatiehypothese stelt dus dat een spinnenmepper niet direct de doelsnelheid gebruikt, maar dat er toch rekening wordt gehouden met de doelsnelheid in het handpad door het gebruik van de verkeerd waargenomen doelpositie (die immers informatie bevat over de doelsnelheid). De tweede hypothese is de *hypothese van toenemend snelheidsgebruik*. Volgens deze hypothese verandert de gebruikte snelheid van de default snelheid in de echte snelheid. Als een doel kort zichtbaar is, is de proefpersoon niet in staat om de echte snelheid goed waar te nemen en hij of zij zal een snelheid gebruiken die tussen de default en de echte snelheid in ligt.

We maakten van iedere hypothese een model dat de afstand voorspelde die de spin rende gedurende de tijd tussen het verdwijnen van de spin en aankomst van het stokje op het scherm. Voor elk model fitten we een parameter; de extrapolatietijd voor de extrapolatiehypothese en de tijd waarop het gebruik van de default snelheid veranderde in de echte snelheid voor de hypothese van toenemend snelheidsgebruik. De uitkomsten werden vergeleken met de afstanden die de proefpersonen werkelijk voor het verdwijnpunt sloegen. De modellen bleken even goed te presteren.

Met de resultaten van het eerste experiment van hoofdstuk 3 konden we geen onderscheid maken tussen de twee nieuwe hypotheses. De extrapolatiehypothese beschouwt de tijd tussen het verdwijnen van de spin en de aankomst van het stokje op het scherm (de tijd dat de spin *onzichtbaar* is) als cruciaal. Als de spin kort onzichtbaar is kunnen proefpersonen relatief lang gebruik maken van de doelsnelheid; is hij lang onzichtbaar, dan zullen ze vooral gebruik maken van de default snelheid. De hypothese van toenemend snelheidsgebruik beschouwt echter de tijd dat de spin *zichtbaar* is als de bepalende factor; hoe langer de spin zichtbaar is, hoe meer er gebruik gemaakt kan worden van de doelsnelheid. In het eerste experiment waren spinnen die lang zichtbaar waren altijd kort onzichtbaar en andersom, dus we weten niet wat de bepalende factor is; worden spinnen die lang zichtbaar zijn beter geslagen omdat ze lang zichtbaar zijn of omdat ze kort onzichtbaar zijn?

In het tweede experiment mochten proefpersonen pas beginnen met slaan nadat ze een toon hadden gehoord. Op deze manier konden we kort en lang zichtbare spinnen presenteren, maar met dezelfde tijd tussen het verdwijnen en de aankomst van het stokje op het scherm. Zoals je volgens de extrapolatiehypothese zou verwachten, werden beide soorten spinnen even goed geslagen. De hypothese van toenemend gebruik van snelheid voorspelde foutief dat de lang zichtbare spinnen beter zouden worden geslagen. Er werden ook spinnen gepresenteerd die altijd lang genoeg zichtbaar waren om de proefpersonen de gelegenheid te geven de echte snelheid te gebruiken, maar de ene soort spin verdween terwijl de andere soort spin altijd zichtbaar bleef. De voorspelling van de extrapolatiehypothese bleek te kloppen: de spin die altijd zichtbaar bleef werd beter geslagen terwijl de hypothese van toenemend gebruik van snelheid ongelijk had met de voorspelling dat beide soorten spinnen even goed zouden worden geslagen. De resultaten waren echter niet erg duidelijk. Het kwantitatieve model van de extrapolatiehypothese voorspelde de resultaten van het tweede experiment ook niet beter dan het model van toenemend gebruik van snelheid.

We voerden een derde experiment uit om nog op een andere manier te testen of de doelsnelheid zelf wordt gebruikt in het bepalen van de eindpositie van het stokje. De proefpersonen sloegen weer verdwijnende spinnen, maar deze keer kon de achtergrond waarover de spinnen renden bewegen. Als de achtergrond tegen de bewegingsrichting van de spinnen in beweegt lijken de spinnen sneller, terwijl ze langzamer lijken als de achtergrond in dezelfde richting als de spinnen beweegt. Als de doelsnelheid wordt gebruikt zouden de proefpersonen verder voor het verdwijnpunt moeten slaan als de spin snel lijkt te bewegen dan als hij langzaam lijkt te bewegen. Dit bleek niet zo te zijn.

Uit de experimenten van hoofdstuk 3 concluderen we dat, hoewel de doelsnelheid de eindpositie van het stokje beïnvloedt, proefpersonen de waargenomen snelheid niet gebruiken in het sturen van het handpad. Het effect van de doelsnelheid zou voort kunnen komen uit een snelheidsgerelateerde fout van de doelpositie.

Hoofdstuk 4 - Kan versnelling worden gebruikt in onderscheppingstaken?

In hoofdstuk 4 wordt de vraag behandeld of het mogelijk is informatie over versnelling te gebruiken in het onderscheppen van bewegende voorwerpen.

Omdat de meeste onderscheppingstaken snelle reacties vereisen, zou versnelling snel gedetecteerd moeten worden om deze informatie te kunnen gebruiken. De detectiedrempels voor versnelling die worden beschreven in de literatuur zijn echter gebaseerd op lang gepresenteerde stimuli. Het is de vraag of je deze drempels mag gebruiken als je iets wilt zeggen over het gebruik van versnelling in onderscheppingstaken zoals Port, Lee, Dassonville en Georgopoulos (1997) dat hebben gedaan. Zij lieten proefpersonen versnellende doelen onderscheppen op een computer monitor met een cursor die de proefpersonen bestuurden met een muis. Port et al. beweerden dat de versnellingen detecteerbaar waren, maar dat proefpersonen deze informatie niet gebruikten. De detectiedrempel voor versnelling zou echter hoger uit kunnen vallen dan de drempels uit de literatuur als kort gepresenteerde stimuli zouden zijn gebruikt. Als dat zo is hebben de proefpersonen in het experiment van Port et al. versnelling misschien alleen niet gebruikt omdat zij die niet konden detecteren. Daarom hebben wij gemeten hoe goed proefpersonen versnelling kunnen detecteren met kort gepresenteerde stimuli.

De proefpersonen voerden twee taken uit waarin zowel de presentatietijd van de stimulus als de gemiddelde snelheid werden gevarieerd. In de vergelijkingstaak presenteerden we twee opeenvolgende dots; de ene dot versnelde en de andere vertraagde. De proefpersoon werd gevraagd aan te geven welke dot versnelde. In de instellingstaak moest de proefpersoon met behulp van de muis de beweging van een aanvankelijk versnellende of vertragende dot zó aanpassen dat de dot met een constante snelheid leek te bewegen. Deze taak had als voordeel dat een mogelijke bias onthuld zou kunnen worden in wat proefpersonen als constante snelheid zien. We vonden slechts in één van de negen condities een significante afwijking van de constante snelheid. Uit de resultaten van de vergelijkingstaak bleek dat de meeste proefpersonen al versnelling konden detecteren bij een presentatietijd van 300 ms. Zij namen echter niet de versnelling zelf waar (d.w.z., de snelheid waarmee de snelheid verandert), zij leken eerder de snelheid aan het begin van de presentatie met die aan het eind te vergelijken en op deze manier te detecteren of de stimulus versnelde of vertraagde. Dit bleek uit het feit dat de drempels in beide taken sterk werden beïnvloed door presentatietijd en gemiddelde snelheid als zij werden uitgedrukt in versnelling (de drempels namen af met presentatietijd en namen toe met gemiddelde snelheid) terwijl de presentatietijd en gemiddelde snelheid de detectiedrempels minder of niet beïnvloedden als zij werden uitgedrukt in percentage snelheidsverandering. Dit is al eerder gevonden. Versnelling kon redelijk goed worden gedetecteerd bij een snelheidsverandering van 25%, wat weinig is in vergelijking met drempels uit andere studies.

Hiermee hebben we de claim van Port et al. (1997) bevestigd dat de versnellingen van hun stimuli detecteerbaar waren; de gepresenteerde versnellingen lagen boven de detectiedrempel zoals gemeten met korte presentatietijden. Het lijkt erop dat versnelling inderdaad niet gebruikt wordt bij dit soort onderscheppingstaken.

Voor een andere onderscheppingstaak is beweerd dat versnelling op een andere, simpele manier gebruikt wordt. Deze taak is het vangen van ballen die de vanger naderen langs een parabolisch pad. In dit geval is de relatie tussen de versnelling van het doel en de optische hoekversnelling behoorlijk ingewikkeld. Toch kan het detecteren van hoekversnelling nuttig zijn omdat die informatie bevat over de plek waar de bal gaat landen: de projectie van de bal op een vlak versnelt als de bal achter je zal landen, terwijl het vertraagt als de bal voor je gaat landen (zie Figuur 4-5). Om te bepalen of ze naar voren of naar achteren moeten beginnen te rennen, hoeven balvangers dus alleen maar te detecteren of de projectie versnelt of vertraagt. Als deze strategie inderdaad wordt gebruikt, kunnen balvangers pas beginnen met rennen nádat ze dit hebben gedetecteerd. Wij bepaalden of dat het geval is door de data van Oudejans, Michaels en Bakker (1997) te analyseren. Oudejans et al. lieten proefpersonen ballen vangen en registreerden naast de voet- en hoofdreactietijden van de proefpersoon ook de tijd dat de bal in de lucht was en de afstand die de bal aflegde. Zodoende konden we voor iedere trial de reactietijd vergelijken met de tijd dat de snelheid van de projectie van de bal met 25% was veranderd. Het bleek dat de proefpersonen in veruit de meeste trials hun voet al bewogen vóórdat zij het verschil tussen versnelling en vertraging hadden kunnen detecteren. De beweging van de voet was de eerst meetbare beweging van de proefpersoon. Misschien hadden de proefpersonen tegen die tijd nog niet bepaald welke kant ze uit zouden lopen. We vergeleken dus ook de hoofdreactietijd met de tijd dat de drempel werd bereikt. Weer bleek dat de reactietijd in veel trials korter was dan de tijd dat de drempel werd bereikt. Merk op dat onze drempel van 25% snelheidsverandering een lage schatting is en dat het een 75% correct drempel is, terwijl de balvangers in 97% van de trials de goede kant uit liepen. Verder hebben balvangers na het detecteren van de versnelling of vertraging van de projectie nog tijd nodig om te beginnen met bewegen. Onafhankelijk van de hoogte van de detectiedrempel voor versnelling zou, volgens de hypothese dat balvangers versnelling gebruiken, de tijd dat 25% snelheidsverandering bereikt wordt positief gecorreleerd moeten zijn met de reactietijd. Dat is niet het geval. Wij concludeerden dat balvangers de versnelling van de projectie van de bal niet gebruiken om de looprichting te bepalen.

Wij stellen een andere manier voor waarop de looprichting bepaald zou kunnen worden. De afstand die een bal af zal leggen, uitgedrukt als de proportie van de afstand tussen het startpunt van de bal en het startpunt van de vanger, kan worden berekend uit 1. de afstand tussen het startpunt van de bal en het startpunt van de vanger, 2. de zwaartekrachtversnelling, 3. de verticale startsnelheid van de bal en 4. de horizontale snelheid van de bal. Deze 'geometrisch voorspelde afstand' is lager dan 1 als de bal voor de vanger zal landen en hoger dan 1 als de bal achter zal landen. Heeft een balvanger toegang tot deze vier informatiebronnen? We namen aan dat de afstand tussen het startpunt van de bal en het startpunt van de vanger goed zou kunnen worden geschat, in ieder geval in het experiment van Oudejans et al. waarin deze afstand niet varieerde. We namen ook aan dat mensen (onbewust) kennis hebben van de zwaartekrachtversnelling. Balvangers hebben niet zomaar toegang tot de verticale startsnelheid van de bal en de horizontale snelheid van de bal. Deze kunnen echter geschat worden met behulp van respectievelijk de hoeksnelheid en de expansiesnelheid van de projectie van de bal. We vervingen de horizontale en verticale snelheid van de bal in de formule van de geometrisch voorspelde afstand door deze schattingen en berekenden de hieruit volgende 'waarneembare voorspelde afstand' voor elke bal in het experiment van Oudejans et al. Deze maat bleek het onderscheid te kunnen maken tussen ballen die voor en achter de proefpersonen landden. Als je rekening houdt met detectiedrempels voor hoeksnelheid en expansiesnelheid uit de literatuur, zouden proefpersonen in staat moeten zijn geweest om het verschil tussen ballen die voor en achter hen landen te detecteren voor 95% van de ballen in het experiment van Oudejans et al., 100 ms na het begin van de vlucht. Na 100 ms is er geen enkele bal waarvan de projectie 25% in snelheid is veranderd. We concluderen dat de proefpersonen in het experiment van Oudejans et al. de waarneembare voorspelde afstand kunnen hebben gebruikt om hun startrichting te bepalen.

Hoofdstuk 5 - Is er steun voor het gebruik van taukoppeling bij het onderscheppen van bewegende doelen?

In hoofdstuk 5 testten we de methode die Lee en zijn collega's hebben gebruikt om bewijs te vinden voor de taukoppelingstheorie voor waarnemingsgestuurd gedrag. Deze theorie is gebaseerd op de optische variabele tau. Tau kan worden gedefinieerd als de tijd die nodig is voor de sluiting van een kloof gegeven de huidige sluitingssnelheid. Volgens de taukoppelingstheorie koppelen mensen (en dieren) de tau van de ene sluitende kloof aan de tau van een andere sluitende kloof om doelgericht gedrag uit te voeren. Het 'koppelen' van twee taus betekent de taus in een constante verhouding houden, zodat ze tegelijk nul worden. Een 'kloof' is het verschil tussen de huidige staat en een doelstaat. Deze kloof kan in elke dimensie worden uitgedrukt, zoals afstand, hoek en kracht. Allerlei soorten gedrag kunnen worden beschreven (en zijn ook beschreven) in termen van taukoppeling.

Wij richtten ons op een studie van Lee, Georgopoulos, Clark, Craig en Port (2001) waarin proefpersonen een cursor bestuurden om een doel te onderscheppen op het moment dat dit doel een bepaalde goalzone op een computerscherm bereikte. In deze situatie kunnen drie sluitende kloven worden onderscheiden: hand-goal, doel-goal en hand-doel (Figuur 5-1A en 5-1B). Deze drie kloven sluiten tegelijk als de proefpersoon het doel met succes in de goalzone onderschept. De hypothese van Lee et al. was dat proefpersonen de tau van de sluitende kloof tussen hand en goal (τ_{hg}) koppelden aan de tau van de sluitende kloof tussen doel en goal (τ_{dg}) of aan de tau van de sluitende kloof tussen hand en doel (τ_{hd}). Er werden doelen gepresenteerd met verschillende bewegingstijden. De doelen versnelden, vertraagden of bewogen met een constante snelheid. Voor iedere trial waarin een doel met succes werd onderschept werden taus berekend voor elke 10 ms van de beweging. Vervolgens plotte Lee et al. τ_{hg} tegen τ_{dg} en τ_{hg} tegen τ_{hd}. Aan het eind van de beweging (zodra de tauwaarden nul naderden) vormden zij een rechte lijn, wat duidt op een vaste ratio tussen de taus. Dit was vooral duidelijk in de τ_{hg} - τ_{hd} plot. Lee et al. concludeerden dat proefpersonen τ_{hg} aan τ_{hd} koppelden om doelen te onderscheppen. Zij merkten ook op dat de handsnelheidsprofielen beïnvloed werden door het doelbewegingstype (versnellend, vertragend of constante snelheid). Hieruit concludeerden zij dat proefpersonen hun hand niet in één enkele beweging (ballistisch) naar de goalzone bewogen na het (goed) voorspellen van de aankomsttijd van het doel in de goalzone.

Wij vroegen ons af in hoeverre élke succesvolle gladde beweging tot tauplots zou leiden waarin de datapunten samenkomen in een rechte lijn. We modelleerden ballistische handbewegingen naar doelen zoals die gebruikt werden door Lee et al. Als de methode van Lee et al. juist is en als we deze methode toepassen op de gesimuleerde data, dan zou de taukoppelingshypothese verworpen moeten worden aangezien de gesimuleerde data niet in overeenstemming zijn met taukoppeling.

Het bleek echter dat de datapunten in tauplots van onze gesimuleerde data ook in een rechte lijn samenkwamen. Onze tauplots leken erg op de tauplots van Lee et al. Blijkbaar wijst een constante tauratio aan het eind van een beweging niet op het gebruik van taukoppeling. Onze conclusie is dat Lee et al. (2001) geen steun hebben gevonden voor taukoppeling. In andere studies waarin wordt beweerd dat steun voor taukoppeling is gevonden, werden soortgelijke methoden gebruikt als in Lee et al. (2001). Het is dus twijfelachtig of deze studies daadwerkelijk aanwijzingen leveren voor het gebruik van taukoppeling. In hoofdstuk 5 beschrijven we ook nog enkele problemen van het algemene idee van taukoppeling (als een strategie voor het onderscheppen van bewegende voorwerpen). Een van de problemen is dat er geen rekening wordt gehouden met de tijd die nodig is om informatie te detecteren en acties te plannen en uit te voeren. Zonder het voorspellen van toekomstige waarden van tau is het onmogelijk om de ene tau in een vaste proportie van een andere tau te houden. Voor veel taken is het ook onduidelijk hoe tau eigenlijk kan worden waargenomen.

Algemene conclusies en opmerkingen

Niet alle visuele informatie wordt gebruikt

Visuele informatie, die nuttig zou kunnen zijn en beschikbaar is voor een ideale waarnemer, wordt niet altijd gebruikt voor (bepaalde aspecten van) het onderscheppen van bewegende voorwerpen. In sommige gevallen is dit niet verwonderlijk omdat mensen niet gevoelig zijn voor die informatie. In andere gevallen is men niet gevoelig genoeg. Tenslotte kan bepaalde informatie heel goed worden gedetecteerd, maar gebruikt men deze toch niet voor bepaalde aspecten van de beweging. Voor elk van deze drie categorieën zal ik voorbeelden geven uit dit proefschrift.

In hoofdstuk 5 hebben we de methode getest die gebruikt is om aanwijzingen te vinden voor de taukoppelingstheorie (Lee, 1998). Deze methode bleek onjuist te zijn. We hebben niet direct onderzocht of mensen gevoelig zijn voor de tau van een sluitende kloof en of dat gebruikt wordt in het sturen van beweging. Toch lijkt het mij onwaarschijnlijk dat, in ieder geval in taken als het slaan van spinnen, de taus van sluitende kloven die relevant zouden zijn kunnen worden gedetecteerd. Bij het slaan van spinnen (en in veel andere taken) is de positie waar een doel wordt onderschept niet visueel gemarkeerd. Het is dus moeilijk voor te stellen hoe bijvoorbeeld de tau van de kloof tussen de hand en de plek waar het doel wordt onderschept gedetecteerd kan worden. Als deze informatie niet kan worden gedetecteerd kan het ook niet worden gebruikt. In hoofdstuk 4 toonden we aan dat je versnelling (de snelheid van het veranderen van snelheid) niet kunt waarnemen (dit was ook al gevonden door Schmerler, 1976; Gottsdanker, Frick & Lockard, 1961; Calderone & Kaiser, 1989). Je zal dus (waarschijnlijk) ook niet in staat zijn versnelling te gebruiken in het onderscheppen van bewegende voorwerpen, in de zin van het precies voorspellen waar een versnellend voorwerp zal zijn na een bepaalde tijd.

In hoofdstuk 4 lieten we zien dat, hoewel versnelling niet kan worden waargenomen, men versnelling wel kan detecteren door het vergelijken van snelheden. Echter, men blijkt niet gevoelig genoeg te zijn voor snelheidsverandering om dit te kunnen gebruiken voor het bepalen van de looprichting in het vangen van ballen. In principe hoeft een balvanger alleen maar te bepalen of de projectie van een bal vertraagt of versnelt om te weten of hij of zij respectievelijk naar voren of naar achteren moet lopen. Onze resultaten toonden aan dat balvangers in een onderzoek van Oudejans, Michaels en Bakker (1997) een andere informatiebron moeten hebben gebruikt aangezien zij al in de goede richting begonnen te rennen voordat de snelheidsverandering groot genoeg was om te kunnen worden gedetecteerd.

We vonden twee informatiebronnen die proefpersonen op tijd zouden moeten hebben gedetecteerd, maar die zij toch niet gebruikten in (een bepaald deel van) de onderscheppingsbeweging. Het effect van de spinsnelheid op de handsnelheid (hoofdstuk 2) toonde aan dat de snelheid van rennende spinnen detecteerbaar was. De experimenten van hoofdstuk 3 toonden echter aan dat de spinsnelheid niet werd gebruikt in het sturen van het handpad. In de taak van Port, Lee, Dassonville en Georgopoulos (1997) onderschepten proefpersonen versnellende en vertragende doelen op een bepaalde voorgeschreven positie op een scherm. Wij lieten zien dat de snelheidsverandering groot genoeg was om te kunnen worden gedetecteerd (hoofdstuk 4). Proefpersonen hadden dus kunnen compenseren voor versnelling en vertraging van het doel door de aankomsttijd op de goalpositie aan te passen. Toch kwamen proefpersonen te vroeg aan op de goalpositie als het doel vertraagde en te laat als het doel versnelde. Dit geeft aan dat de proefpersonen het onderscheid tussen versnelling en vertraging niet (volledig) gebruikten in deze taak.

Onderscheid tussen het regelen van tijd en plaats

In het onderscheppen van bewegende voorwerpen bepaalt de *combinatie* van het temporele aspect (zoals reactietijd en bewegingstijd) en het spatiële aspect (zoals het handpad) van de actie of het doel met succes wordt onderschept of niet. Je kan hetzelfde doel op verschillende plaatsen onderscheppen als je de timing daarop afstemt en doelen kunnen met verschillende reactie- en bewegingstijden worden onderschept als de plaats van het onderscheppen wordt aangepast. Je zou hieruit kunnen concluderen dat de temporele en spatiële aspecten van de actie niet als aparte eenheden onderzocht zouden moeten worden. Toch denk ik dat het belangrijk is deze aspecten (ook) onafhankelijk van elkaar te bekijken. Ten eerste wordt dit gesuggereerd door onze bevinding dat de doelsnelheid wel wordt gebruikt in de handsnelheid (hoofdstuk 2) maar niet in het sturen van het handpad (hoofdstuk 3). Ten tweede hebben we in hoofdstuk 2 beschreven hoe de handsnelheid de temporele en spatiële nauwkeurigheid verschillend beïnvloedt: een snelle beweging zorgt waarschijnlijk voor een hoge nauwkeurigheid in timing terwijl de spatiële nauwkeurigheid juist lager wordt. Dit zou kunnen verklaren waarom je beter sneller naar snelle doelen kunt bewegen dan naar langzame (deze verklaring wordt ook ondersteund door Tresilian en Lonergan, 2002, en Brenner, de Lussanet en Smeets, in druk).

Voorspellen van toekomstige doelposities?

Zoals al eerder in dit proefschrift naar voren is gekomen, moet er in iedere onderscheppingstaak rekening gehouden worden met de beweging van het doel tijdens het plannen en uitvoeren van de eigen beweging. Het lijkt noodzakelijk om de toekomstige posities van een bewegend doel over de tijd te voorspellen. Sommige auteurs (die de ecologische benadering ondersteunen) vinden dit 'voorspellen' echter onwaarschijnlijk. Zij betwijfelen of de informatie die de vanger of mepper tot zijn of haar beschikking heeft voldoende nauwkeurig is (Peper, Bootsma, Mestre & Bakker, 1994; McLeod & Dienes, 1996) of vinden voorspellen omslachtig en gevoelig voor (reken)fouten (Montagne, Laurent, Durey & Bootsma, 1999). Er bestaan onderscheppingsmodellen waarin geen toekomstige posities van het doel voorspeld worden (Chapman, 1968; Lee, 1998; McBeath, Shaffer & Kaiser, 1995; Peper et al., 1994; Zaal, Bootsma & van Wieringen, 1999). Volgens deze zogenaamde voortdurende controle modellen vormen en onderhouden proefpersonen een bepaalde relatie tussen het doel en de onderscheppingsbeweging totdat de onderschepping 'automatisch' plaatsvindt. De experimentele resultaten die deze modellen verwachten worden vaak gecontrasteerd met resultaten die zouden worden verwacht als de vangers of meppers de plaats waar het doel wordt onderschept perfect zouden voorspellen, meteen aan het begin van de beweging van het doel. Het is bijvoorbeeld gesuggereerd dat als proefpersonen de plaats van onderschepping voorspellen, zij altijd op precies dezelfde manier naar deze plaats zouden bewegen, onafhankelijk van de bewegingsrichting of snelheid van het doel (tenminste, als de beweging van de proefpersonen altijd vanuit hetzelfde punt begint; Peper et al., 1994; Montagne et al., 1999, Lee et al. 2001). Een ander voorbeeld is het idee dat balvangers die de plek voorspellen waar de bal landt, onmiddellijk en snel naar de goede plek zouden rennen (McLeod & Dienes, 1996; Oudejans, Michaels & Bakker, 1997).

In dit proefschrift zijn twee van de modellen, die het onderscheppen van bewegende voorwerpen beschrijven zonder toekomstige doelposities te voorspellen, nader bekeken. Deze twee modellen zijn het zodanig rennen dat de projectie van een bal met een constante snelheid beweegt (hoofdstuk 4) en taukoppeling[5] (hoofdstuk 5). Het eerstgenoemde model is afgewezen en de methode die steun leek te bieden aan het tweede model bleek onjuist. Andere voortdurende controle modellen zijn complex en moeilijk te testen (Peper et al., 1994; Zaal, Bootsma & van Wieringen, 1999).

Naast het feit dat wij geen steun hebben kunnen vinden voor twee voortdurende controle modellen, is het duidelijk dat alléén het koppelen van beweging aan visuele informatie niet genoeg kan zijn om onderscheppingstaken uit te voeren. Dit blijkt uit hoofdstuk 3, waarin we hebben laten zien dat je een spin met succes kunt slaan, ook als er tijdelijk geen visuele informatie over de spin beschikbaar is. Verder kun je rekening houden met informatie over voorgaande doelen (Button, Davids, Bennett & Savelsbergh, 2002; de Lussanet, Smeets & Brenner, 2001). Het is ook duidelijk dat als de plaats waar het doel wordt onderschept voorspeld wordt, dit geen perfecte voorspelling zal zijn die onmiddellijk beschikbaar is. Een voorspelling die steeds wordt verbeterd gedurende de onderscheppingsbeweging zou een meer waarschijnlijke manier van voorspellen zijn. Op deze manier hoeft voorspellen ook niet complex te zijn. In hoofdstuk 3 gaven we een voorbeeld van wat je een 'automatisch' gegenereerde voorspelling zou kunnen noemen; het verkeerd waarnemen van een bewegend doel in de bewegingsrichting. Samengevat ben ik van mening dat het niet nodig en niet gerechtvaardigd is om het idee van voorspellen bij voorbaat uit te sluiten.

Meerdere bronnen van informatie; verschillen tussen situaties en proefpersonen

Voor het onderzoek dat is beschreven in dit proefschrift waren we geïnteresseerd in het *algemene* gedrag van gezonde proefpersonen. De vraag naar het gebruik van visuele informatie in het onderscheppen van bewegende doelen werd benaderd alsof er één of twee bepaalde informatiebronnen zijn, die wel of niet door elke proefpersoon gebruikt worden om een bepaalde actie (of een bepaald aspect ervan) te sturen. We namen aan dat in taken als het slaan van een spin, dat plaatsvindt binnen een seconde en waarbij er waarschijnlijk niet veel verschillende informatiebronnen aanwezig zijn, het gedrag van mensen niet erg varieert.

In het algemeen geldt dat hoe ingewikkelder een taak is en hoe meer informatiebronnen beschikbaar zijn, hoe groter het effect van strategie, leren en verschillen

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[5] Als de plaats waar het doel wordt onderschept niet visueel gemarkeerd is, wordt er eigenlijk toch voorspelling verondersteld in het koppelen van de tau van de kloof tussen de hand en de plaats waar het doel wordt onderschept aan de tau van een andere kloof; immers, de plaats waar het doel wordt onderschept moet een toekomstige positie van het doel zijn.

tussen proefpersonen zal zijn. Verscheidene studies geven aan dat mensen meerdere informatiebronnen gebruiken om hun gedrag te sturen (Michaels, Zeinstra & Oudejans, 2001; Rushton & Wann, 1999; van der Kamp, Savelsbergh & Smeets, 1997; Michaels & Oudejans, 1992). Welke bronnen (het meest) worden gebruikt zal afhangen van de taak en van de ervaring, kennis en algemene vaardigheden van de proefpersoon. Dit betekent niet dat gedrag in ingewikkelde taken niet kan worden onderzocht. Als je echter een taak gebruikt die 'ingewikkeld' zou kunnen zijn moet je wel in gedachten houden dat factoren als strategie en leren een rol kunnen spelen, en altijd controleren of de data er hetzelfde uitziet tussen proefpersonen en gedurende het verloop van het experiment voordat je conclusies trekt uit de gemiddelde data.

Een voorbeeld van het gebruik van meerdere informatiebronnen over verschillende situaties is het vangen van ballen met één of twee ogen open. Proefpersonen zouden binoculaire informatie kunnen gebruiken (als de bal dichtbij is), maar zij vertrouwen in ieder geval niet altijd alleen op deze informatiebron, wat blijkt uit het feit dat mensen met één oog open toch ballen kunnen vangen (van der Kamp, Savelsbergh & Smeets, 1997). Zoals al opgemerkt in de introductie, gebruiken zelfs vangers die met twee ogen kijken niet altijd binoculaire informatie als het baltraject erg voorspelbaar is (Servos & Goodale, 1998) en als er duidelijkere informatiebronnen aanwezig zijn (Rushton & Wann, 1999).

Een studie van Michaels en Oudejans (1992) illustreert het gebruik van meerdere informatiebronnen over verschillende proefpersonen. Michaels en Oudejans simuleerden ballen op een computerscherm en lieten proefpersonen beoordelen of de bal voor of achter hen zou landen. De resultaten suggereerden dat verschillende proefpersonen de voorkeur gaven aan het gebruik van verschillende optische variabelen. Hoewel het het meest effectief zou zijn geweest om de bal als 'voor' te beoordelen als de gesimuleerde projectie van de bal vertraagde en 'achter' als deze versnelde, bleken veel proefpersonen de hoogte of de maximale snelheid van de gesimuleerde projectie te gebruiken. Als de proefpersonen feedback hadden gekregen en als deze variabelen niet waren gecorreleerd met de landingspositie (zoals het geval was in het experiment van Michaels en Oudejans), zouden zij waarschijnlijk minder gebruik hebben gemaakt van deze variabelen.

In dit proefschrift zijn verschillen tussen proefpersonen niet benadrukt, maar ze zijn af en toe naar voren gekomen. In hoofdstuk 2 bleek dat sommige proefpersonen spinnen snel sloegen met weinig snelheidskoppeling, terwijl anderen er de voorkeur aan gaven de spinnen langzaam te slaan met veel snelheidskoppeling. Er waren ook verschillen in hoe goed versnelling gedetecteerd kon worden (hoofdstuk 4); drie van de tien proefpersonen presteerden niet goed genoeg om hun data te kunnen analyseren. In hoofdstuk 4 is ook het verschil tussen ervaren en niet-ervaren balvangers genoemd dat Oudejans, Michaels en Bakker (1997) hadden opgemerkt. Ervaren vangers waren veel beter in het kiezen van de juiste looprichting dan de niet-ervaren vangers. Dit geeft aan dat mensen in dit geval moeten leren om de meest relevante visuele informatiebronnen te detecteren en op een juiste manier te gebruiken. McLeod (1987) betoogt dat bij het slaan van een cricketbal, het grootste verschil tussen ervaren en niet-ervaren spelers in het uitvoeren van de motortaak ligt. Het lijkt er echter op dat ook in deze taak ervaren spelers de visuele informatie beter kunnen gebruiken om te voorspellen waar en wanneer de bal hen bereikt dan niet-ervaren spelers zoals weerspiegeld in verschillend oogmotorisch gedrag (Land & McLeod, 2000).

Een globale manier waarop visuele informatie gebruikt kan worden in het onderscheppen van bewegende doelen

Zoals al naar voren is gekomen, zijn de visuele informatie die wordt gebruikt voor het onderscheppen van bewegende doelen en de soort beweging die uitgevoerd moet worden sterk taakafhankelijk. Verder verschilt de ervaring en de gebruikte strategie tussen proefpersonen en situaties. Hierdoor is het onmogelijk om een simpele theorie in elkaar te zetten die precies beschrijft welke visuele informatie op welke manier gebruikt wordt voor elke onderscheppingstaak. Ik kan echter samenvatten wat hiervoor in dit proefschrift is gesteld en een algemeen idee geven van hoe het zou kunnen werken.

Het zal onmogelijk zijn om meteen aan het begin van de beweging van het doel exact te voorspellen waar en wanneer het doel zal worden onderschept, vanwege beperkingen die zijn opgelegd door visuele detectiedrempels en het vermogen van het brein om dingen 'exact' te berekenen (zeker gegeven de beperkte beschikbare tijd). Een exacte voorspelling is ook onwaarschijnlijk gezien onze bevinding dat niet alle informatie die hier nuttig voor kan zijn ook echt gebruikt wordt. Een alternatief kan zijn dat je om een bewegend doel te onderscheppen, een ruwe schatting maakt van waar en wanneer je het doel zult onderscheppen en deze schatting steeds verbetert met behulp van nieuwe, bijgewerkte informatie over het doel en het lichaamsdeel (inclusief het eventuele slagwapen) waarmee je het doel wilt onderscheppen. Op deze manier kun je relatief makkelijk rekening houden met onverwachte bewegingen van het doel. Impliciete kennis, verkregen door ervaring (bijvoorbeeld over de zwaartekrachtversnelling of de betrouwbaarheid van verschillende informatiebronnen) zal bijdragen aan een goede schatting. Verschillende informatiebronnen kunnen gebruikt worden om verschillende aspecten van de beweging te controleren. De snelheid van een snelle spin kan de spinnenmepper doen besluiten snel te slaan. De (verkeerd) waargenomen positie van de spin kan worden gebruikt om de passende eindpositie van het slagstokje te bepalen.

Toekomstige experimenten

Het is duidelijk dat veel vragen over het gebruik van visuele informatie in het onderscheppen van bewegende voorwerpen onbeantwoord blijven. Met betrekking tot het onderzoek dat is beschreven in dit proefschrift zou het vooral interessant zijn om de geldigheid van de nieuwe hypotheses die zijn voorgesteld in hoofdstuk 2, hoofdstuk 3 en hoofdstuk 4 te toetsen.

In hoofdstuk 2 hebben we voorgesteld dat mensen sneller bewegen naar snelle doelen dan naar langzame, omdat een nauwkeurige timing relatief belangrijker is voor snelle doelen en omdat de nauwkeurigheid in timing verbetert door snel te bewegen. Dit snelle bewegen gaat ten koste van de spatiële nauwkeurigheid. Deze hypothese kan getoetst worden met een experimentele opzet waarin het belang van nauwkeurigheid in tijd en plaats gemakkelijk en systematisch kan worden gevarieerd. Je zou proefpersonen bijvoorbeeld een doel kunnen presenteren dat afwisselend 'aan' en 'uit' is voor vaste tijdsintervallen. De proefpersonen wordt dan gevraagd zo lang ze willen naar het doel te kijken en het doel dan te slaan terwijl het aan is. De nauwkeurigheidseis in tijd kan worden gevarieerd door de tijd dat het doel aan is te veranderen, en de nauwkeurigheidseis in plaats kan worden gevarieerd door de grootte van het doel te veranderen. De hypothese voorspelt dat doelen van gelijke grootte met een snellere beweging worden geslagen als ze kort aan zijn dan als ze lang aan zijn. Naarmate het doel groter wordt zal de bewegingssnelheid verder toenemen (tot een bepaalde grens).

In hoofdstuk 3 hebben we voorgesteld dat het effect van doelsnelheid wordt veroorzaakt door een snelheidsgerelateerde fout in het waarnemen van de doelpositie. Volgens Brenner et al. (2001) ontstaat deze fout door het combineren van binnenkomende retinale signalen met uitgaande oogbewegingscommando's. Met andere woorden, je ziet het doel op de plaats waar je net je blik heen hebt gestuurd. Als dit zo is, zou er een relatie moeten zijn tussen oogbewegingen en de eindpositie van het slagstokje (in het geval van het slaan van spinnen). Als proefpersonen het doel bijvoorbeeld niet goed volgen zal het effect van de doelsnelheid kleiner moeten zijn dan als ze wel goed volgen. Het zou dus interessant zijn om oogbewegingen te meten tijdens het slaan van (verdwijnende) spinnen.

Hoofdstuk 4 eindigt met het voorstel dat balvangers de waarneembare voorspelde afstand zouden kunnen gebruiken om te bepalen of ze naar voren of naar achteren moeten lopen. We weten dat de waarneembare voorspelde afstand van ballen die hoger komen dan 15 meter redelijk sterk af beginnen te wijken van de afstand die ze daadwerkelijk zullen afleggen. Het gebruik van waarneembare voorspelde afstand voor het bepalen van de looprichting zou kunnen worden onderzocht door eerst systematisch te bepalen welke ballen waarneembare voorspelde afstanden opleveren die sterk afwijken van de echte afstand, en vervolgens te bepalen of balvangers inderdaad moeilijkheden hebben met het bepalen van de juiste looprichting bij deze ballen. Het zou mogelijk kunnen zijn om een balmachine ballen te laten lanceren waarvan de waarneembare voorspelde afstand duidelijk aangeeft dat de balvanger naar achteren moet lopen, terwijl de bal eigenlijk vóór de startpositie van de vanger zal landen (en andersom). We zouden in ieder geval ballen kunnen ordenen op basis van de moeite die balvangers zouden moeten hebben met het kiezen van de juiste looprichting en dit vergelijken met het gedrag van de ervaren balvanger. Tevens zouden we ballen aan ervaren balvangers kunnen presenteren in een virtuele wereld (zoals de CAVE, Zaal & Michaels, 2001) en de waarneembare voorspelde afstand kunnen manipuleren door het aanpassen van de toepasselijke parameters. Als ervaren balvangers deze variabele inderdaad gebruiken, zouden we moeten kunnen voorspellen in welke trials ze verwachten dat de bal voor hen gaat landen en in welke trials achter.

Een onderzoeksonderwerp dat we niet hebben behandeld, hoewel het wel in dit proefschrift zou hebben gepast, is het gebruik van richting in het slaan van doelen die over een frontaal vlak bewegen. Zoals het geval is met snelheid en veranderende positie, lijken ook bewegingsrichting en veranderende positie apart te worden verwerkt ondanks dat zij natuurkundig gezien onlosmakelijk met elkaar zijn verbonden. Smeets en Brenner (1995b) hebben dit laten zien door hun proefpersonen bewegende doelen te presenteren op een achtergrond die loodrecht op de bewegingsrichting van het doel bewoog. De beweging van de achtergrond had geen invloed op de schattingen die de proefpersonen maakten van de doelpositie, maar wel op de geschatte bewegingsrichting van het doel. Het zou interessant zijn om te kijken of proefpersonen, analoog aan onze bevindingen in hoofdstuk 3, alleen de waargenomen positie van het doel en niet de waargenomen bewegingsrichting gebruiken in het bepalen van de plaats waar zij het doel zullen onderscheppen.

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Dankwoord

Inleiding

Er wordt vaak gesuggereerd dat mensen die promotie-onderzoek uitvoeren en een proefschrift schrijven, dit niet kunnen doen zonder steun van anderen. Volgens Raymond Cuijpers (2000) zijn veel mensen betrokken geweest bij de totstandkoming van zijn proefschrift en Marc de Lussanet (2002) stelt zelfs dat het 'vanzelf spreekt' dat vele mensen direct en indirect een belangrijke bijdrage hebben geleverd aan zijn proefschrift. Om dit verschijnsel te onderzoeken hebben we een willekeurige proefpersoon in een uiterst stimulerende omgeving geplaatst met de taak om binnen vier jaar een proefschrift te produceren. De verwachting is dat dit een grote kans van slagen heeft.

Methoden

Proefpersoon

Proefpersoon AM verleende informed consent om tegen een geringe maandelijkse vergoeding mee te werken aan het onderzoek.

Materiaal

De proefpersoon kreeg de beschikking over alle essentiële materialen, zoals een kamer bij de afdeling Fysiologie aan de Erasmus Universiteit Rotterdam, een Optotrack, een magneetbeestje en een druifblauwe Imac uitgerust met Statview en Eudora. In dit onderzoek zijn wij echter vooral geïnteresseerd in de mensen in de omgeving van AM.

De taak van AM werd uitgevoerd onder begeleiding van Eli en Jeroen, bij wie ze altijd binnen kon wandelen met vragen. Eli en Jeroen zaten boordevol met ideeën voor experimenten en analyses en becommentarieerden enthousiast haar ingeleverde stukken. Ook ondersteunden zij AM met een optimistische blik en koekjes bij de thee. AM begon haar eerste dag in Rotterdam samen met John en Jeroen. Zij waren onmisbaar voor de gezelligheid op de vakgroep en tijdens uitjes in het binnen- en buitenland, en vormden lotgenoten als er weer een stuk was becommentarieerd. AM kon Jeroen's bijzondere talent voor het bespreken van onder andere het weekend en het bedenken van spelletjes zeer waarderen. Hoewel AM eigenlijk ook wel eens aan de beurt had mogen zijn bij het gooien van sinaasappels in broadcast-werp-spel. John was altijd zeer behulpzaam bij het oplossen van problemen met de computer (dus dan mag je die ook wel eens flink laten crashen) en was altijd in voor een goed (broadcast-) gesprek. Ook de overige (ex-)leden van de vakgroep waren zeer belangrijk voor de goede sfeer en behulpzaam bij allerlei programmeer-, wiskunde- en computerproblemen. Zij deden zonder morren mee als proefpersoon aan de experimenten van AM. Een zekere twee-eenheid bekommerde zich om AM's conditie en sleepte haar elke week mee naar het sportcentrum bij Woudestein.

Aangezien AM het zeer verhelderend vond om het eigen onderzoek netjes op een rijtje te zetten en inspirerend om over ander onderzoek te horen, was het erg fijn dat naast de vakgroepwerkbesprekingen er de bijeenkomsten waren met 'Amsterdam'; Claire, Frank, Knoek, Raoul en Leonard. Zij waren altijd erg geïnteresseerd en gaven nuttige feedback.

Ook buiten het werk bevond AM zich in een stimulerende omgeving. Joris, Maarten en Pieter waren ook gedurende deze studie erg belangrijk voor AM om over van alles te praten (soms zelfs ook over AM's onderzoek). [6amin den. flapwap l^goo tolumX Zookikyy sultii* Door hen, de Marjoleinen en alle andere vrienden heeft AM een gezellige tijd gehad gedurende het onderzoek. Ook AM's moeder, vader en Hank alsmede de 'schoonfamilie' hebben een belangrijke rol gespeeld in het welzijn van AM tijdens het produceren van het proefschrift.

Andries was natuurlijk onmisbaar voor AM, hij heeft vele proefpraatjes en onderzoeksproblemen aangehoord, daarover meegedacht en werd nooit moe van AM te verzekeren dat ze het wel kon.

Resultaten

AM heeft gedurende deze studie zeer veel geleerd op allerlei gebieden en een proefschrift geproduceerd.

Discussie

Ondanks het kleine aantal proefpersonen in deze studie menen wij toch nieuwe aanwijzingen te hebben gevonden dat bij het uitvoeren van promotie-onderzoek en het schrijven van een proefschrift, mensen die de promovendus wetenschappelijk, technisch, emotioneel en sociaal steunen van een niet te onderschatten belang zijn. AM is daar in ieder geval vast van overtuigd en wil iedereen die op welke manier dan ook heeft bijgedragen heel hartelijk bedanken.

Curriculum Vitae

Anne-Marie Brouwer werd in Doetinchem geboren op 24 september 1975. In 1993 behaalde zij haar VWO-diploma aan het St. Ludger College te Doetinchem. Datzelfde jaar begon zij aan de Katholieke Universiteit Nijmegen met de studie psychologie, met als afstudeerrichting funktieleer. Haar afstudeeronderzoek verrichte zij in samenwerking met Frans Boselie. Zij deed enkele experimenten om het visuele segmentatiemodel van Siddiqi, Tresness en Kimia te toetsen. In 1998 ontving zij haar doctoraal diploma met het predicaat 'met genoegen'. In september van dat jaar begon Anne-Marie met haar promotieonderzoek bij Eli Brenner en Jeroen Smeets op de vakgroep fysiologie van de Erasmus Universiteit Rotterdam. Dit proefschrift is daar het resultaat van.

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