Grasping Oriented Objects

een wetenschappelijke proeve op het gebied van de Natuurwetenschappen,
Wiskunde en Informatica

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# Contents

1 Introduction .................................... 6  
   1.1 Reaching for a target .......................... 8  
   1.2 Object manipulation movements ................. 11  
   1.3 Perception of object orientation ................. 12  
   1.4 Comparing the structures of visual and haptic space .............. 14  
   1.5 Task dependence of haptic space .................. 15  
   1.6 Intercepting oriented objects .................... 17  
   1.7 Conclusion and outlook .......................... 18  

2 Posture-based or trajectory-based movement planning? A comparison of direct and indirect pointing movements 19  
   2.1 Introduction .................................... 20  
   2.2 Method ......................................... 23  
      2.2.1 Experiment .................................. 23  
      2.2.2 Model simulations ............................ 26  
   2.3 Results ........................................ 28  
      2.3.1 Model simulations ............................ 31  
   2.4 Discussion ...................................... 32  

3 Visual and haptic matching of perceived orientations of lines 39  
   3.1 Introduction .................................... 40  
   3.2 Experiment 1 ..................................... 41  
      3.2.1 Method ..................................... 42  
      3.2.2 Results ..................................... 45  
      3.2.3 Discussion .................................. 47  
   3.3 Experiment 2 ..................................... 49  
      3.3.1 Method ..................................... 49  
      3.3.2 Results ..................................... 51  
      3.3.3 Discussion .................................. 53
4 The structure of fronto-parallel haptic space is task dependent

4.1 Introduction .............................................. 62
4.2 Experiment 1 .............................................. 64
  4.2.1 Method ................................................ 65
  4.2.2 Results ................................................. 68
  4.2.3 Discussion ............................................. 73
4.3 Experiment 2 .............................................. 74
  4.3.1 Method ................................................ 75
  4.3.2 Results ................................................. 76
  4.3.3 Discussion ............................................. 78
4.4 Experiment 3 .............................................. 79
  4.4.1 Method ................................................ 79
  4.4.2 Results ................................................. 80
  4.4.3 Discussion ............................................. 81
4.5 General Discussion ...................................... 82

5 Catching oriented objects .................................. 85
5.1 Introduction .............................................. 86
5.2 Experiment 1 .............................................. 88
  5.2.1 Method ................................................ 89
  5.2.2 Results and Discussion .............................. 92
5.3 Experiment 2 .............................................. 94
  5.3.1 Method ................................................ 96
  5.3.2 Results ................................................. 99
  5.3.3 Discussion ............................................. 103
5.4 Experiment 3 .............................................. 106
  5.4.1 Method ................................................ 108
  5.4.2 Results ................................................. 109
  5.4.3 Discussion ............................................. 110
5.5 Conclusions .............................................. 111

Bibliography .................................................. 113
Chapter 1

Introduction
Many human movements involve grasping an object. For a successful grasp the location and orientation of the object has to be perceived. The grasping movement then consists of several phases: the hand has to be transported to the object location, it has to be opened and its orientation has to be changed such that the object can be grasped. The grasp ends with closing the hand. Figure 1.1 shows nine frames from a movie of a participant grasping a bowl. The task of the participant was to grasp the bowl and to move it to a different location with an instructed orientation. The following aspects of the movement can be observed in Figure 1: Start of the movement (1), acceleration of the reaching phase (2, 3, 4), opening of the hand to grasp the object and deceleration (5, 6, 7), closing of the hand to be able to lift the object (8, 9).

Figure 1.1: A participant grasping a salad bowl. Nine successive frames of a video recording of the movement are shown.
1.1 Reaching for a target

In our first study we measured final arm postures of reaching movements, which we compared with predictions of models postulated in the literature. Planning arm movements is not a trivial task, because of the large number of degrees of freedom of the human arm. For each movement that brings the finger tip at the target position, there are many possible arm configurations during the movement and at the end of the movement. For an arm with four possible joint rotations (three rotations in the shoulder and one in the elbow) the arm can reach for a target in 3-D space in many ways. Figure 1.2 shows a robot arm reaching for the same target with three possible end postures. Experiments have shown that repeated movements to the same target are very similar (e.g., Kamper, Cruz, & Siegel, 2003). The observation that end postures and movements are reproducible, despite the large number of degrees of freedom, has led to the suggestion of constraints that might reduce the available number of degrees of freedom. Models of motor control have aimed at describing the constraints that the human motor system uses to plan the arm movement towards the goal position.

Not only at the joint level there many degrees of freedom available. For many movements there are also more muscles in the human arm than strictly necessary to make the movements (Latash, 1989). For example, for flexion of the forearm the brachialis and biceps brachii muscles can be used. A selection must be made to which extent to activate each muscle for a particular movement.

The large number of individual motor neurons suggests that also at this level there is a large degree of freedom in the selection of activated units. Observations suggest that the selection problem at this level is solved by activating neurons in a particular order (Cope & Pinter, 1995). For small loads the smallest motor units (Type I) are activated. When more force has to be produced larger motor units (Type IIb) are also recruited.

An important issue in motor control research has been whether the motor system controls posture (equilibrium control) or force (Latash, 1989). The difference between the two types of control can be illustrated by the situation shown in Figure 1.3. Suppose a sphere is resting on a membrane. The objective is to transport the sphere over the membrane to the target position. In equilibrium control the sphere will be moved by pressing on the membrane along a ‘virtual trajectory’ (Figure 1.3EC). The sphere will then follow the path and end in the target position. According to the same idea, a human arm can be moved to the equilibrium position by changing the rest length of
the muscles. When the muscle is considered to be a spring with a stiffness and a rest length, the rest length can be changed by changing the stiffness. For force control the exact force needed to transport the sphere to the target position is computed. This force is then applied at the sphere such that it reaches the target position (Figure 1.3FC). According to this hypothesis, the exact muscle activations needed for an arm movement are computed. These computed activations are then applied leading to the arm movement towards the target. There is a clear advantage of the equilibrium approach: The end position of the sphere does not depend on small disturbances during its path. Despite its advantages equilibrium control has been abandoned as a mechanism for human motor control. The observed stiffness of the human muscles is not large enough to explain the observed movement trajectories by equilibrium control.

A different classification of motor control models distinguishes between posture-based models and trajectory-based models. In posture-based models, such as the equilibrium control hypothesis, the model by Rosenbaum et al. (a model in which stored postures are used for movement planning; see Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995) and Donders’ law (describing the relationship between upper arm elevation, azimuth, and torsion; see Gielen, Vrijenhoek, Flash, & Neggers, 1997) the end-posture is selected before movement onset. The key idea of posture-based models is that the final posture is selected in a unique way. Therefore, the path taken towards the goal position does not affect the end posture. In contrast, for trajectory-based models a criterion determines the path taken towards the target position. The final arm posture is the result of the selected movement trajectory. Examples of trajectory-based models are the
Figure 1.3: Illustration of equilibrium control (EC) and force control (FC). The objective is to move the sphere over the membrane to the target position (gray sphere). In equilibrium control the sphere is moved over the membrane by pressing on the membrane along a path towards the goal position (along the virtual trajectory) such that the sphere follows the path of the hand. In force control the exact forces are computed which are needed to move the sphere to the target position. The movement is then performed in a ballistic fashion. The illustration of equilibrium control was presented during one of Mark Latash’s lectures (2003) on the neural basis of motor control.

In Chapter 2 we discuss an experiment designed to distinguish between posture-based and trajectory-based experiments. In the experiment participants were asked to point at targets presented on a large projection screen. By varying the path towards the target position (in some trials participants had to move along a via point) and measuring the joint angles we could determine which class of models (posture-based or trajectory-based) best describe pointing movements. We found a small effect of the path towards the goal on the final arm posture, favoring trajectory-based models. However, when the exact predictions of the trajectory-based models from literature were considered, none of the models could accurately describe the data. When the deviations between predicted and observed data were considered, Don-
ders’ law (predicting no effect of the path towards the goal position on the end posture) gave the smallest differences between measured and predicted postures.

Figure 1.4: Illustrations of possible hand movements and object manipulation. A. Pointing. B. Power grasp. C. Precision grasp. D. Writing. E. Bimanual coordination.

1.2 Object manipulation movements

Many issues remain open in the study of human motor control. Figure 1.4 illustrates the large variety of movements humans can perform with their hands. So far, most of the models focused on reaching and pointing movements (Figure 1.4A). One model, the posture-based model by Rosenbaum and colleagues (2001) has been applied to grasping movements. The grasping movements that were modeled used a precision grip (Figure 1.4C). In Figure 1.5A a simulated grasp of a spherical object is shown. The figure shows another important aspect of movement planning: Obstacle avoidance. The hand cannot move to the target via the shortest path, because this path will cause a collision between the fingers and the object. This is shown in Figure 1.5B. The posture-based model has also been applied to writing movements
(Figure 1.4D). Meulenbroek and colleagues from the psychonomics research group in Nijmegen are now working on an extension of the model to 3-D movements. Another challenge will be to model bimanual coordination (Figure 1.4E). Many studies of bimanual coordination focus on the interaction of movements between hands (tapping with two hands in different rhythms and see what stable rhythm the hands will tap after a while) and what tasks cannot be performed simultaneously (such as drawing a circle with the left hand and a square with the right hand). It would be interesting to see how the hands work together to, for example, pour water in a glass or to wash hands.

Figure 1.5: A. Simulation of a grasping movement generated by a demonstration computer program of the posture-based model by Rosenbaum et al. (2001). The computer program was downloaded from Ruud Meulenbroek’s webpage at: http://www.nici.kun.nl/~meulenbroek/. The larger gray disc shows the target. The smaller white discs show the positions of the joints. B. Simulation of a movement in which the shoulder was not rotated sufficiently. The arm collides with the target.

1.3 Perception of object orientation

For the remainder of this thesis we chose to focus on the perception part of oriented object grasping. The perception of object orientation fits within the long tradition of the investigation of visual and haptic (touch) space. Visual
and haptic space are assumed representations of external space based on each of the modalities. The structure of these representations is important in distance estimation, size estimation, parallelity judgments, collinearity judgments and symmetry judgments.

Many of the studies of visual and haptic space have aimed at determining the structure of the space. The space is assumed to be a distorted version of the Euclidean space. Mathematically, the distorted space can be described as a Riemann surface with a certain curvature. The surface of a cone, a cylinder and a sphere are examples of Riemann surfaces. Only the sphere has non-zero Gaussian curvature.

Figure 1.6: Parallel transport of an arrow across a closed path on a sphere.

How the curvature of space can affect object orientation is illustrated in Figure 1.6. This figure shows a curved surface on which an arrow is transported past three points to return on the starting position. The arrow moves along the shortest path on the surface, the geodesic, between each pair of points. The movement of the arrow is done by parallel transport: Between each infinitely small step on the path the orientation of the arrow does not change. At the end of the closed path on the sphere the arrow has changed its orientation. The amount of orientation change is dependent on the curvature of the surface and the size of the surface enclosed by the path. If a closed path would have been followed on a cone or a cylinder, the final orientation of the arrow would not differ from its initial orientation, since the Gaussian curvature of the cone and the cylinder is equal to zero.
The sphere shown in Figure 1.6 illustrates another consequence of the curvature of the surface: The angles of a triangle on the surface don’t add up to 180 degrees. The shown triangle has three 90 degrees angles, which add up to 270 degrees. This property of curved space can be used to measure the curvature of visual and haptic space. Figure 1.7 shows a setup, which can be used to measure the curvature of visual space. An observer is standing in an open field. With a remote control he can adjust the orientation of an arrow placed on a tripod. His task is to adjust the orientation of the arrow such that it seems to be pointing at a sphere placed on another tripod. The location of the two tripods is changed and the task is repeated until for each corner the perceived outgoing arrow orientations are measured. Figure 1.8 shows the possible outcomes of a direct measurement of visual space. If the sum of the angles of the triangle is larger than 180 degrees the curvature of the space is positive (triangle 3). If the sum of the angles of the triangle is smaller than 180 degrees the curvature of space is negative (triangle 1). If the angles add up to 180 degrees the space has zero curvature (triangle 2). Koenderink and colleagues (2000) used the method similar to the method illustrated in Figure 1.7 to measure the curvature of visual space. In their experiment the observer was standing in the middle of the triangle. In their experiment they found a negative curvature for large triangles (sides of 10 m), and a positive curvature for smaller triangles (sides of 2 m).

1.4 Comparing the structures of visual and haptic space

In three studies we investigated some of the remaining open issues in the study of visual and haptic space. A first issue we looked at was the relationship between the structures of visual and haptic space. Earlier results suggested that the structures of visual and haptic space are similar. However, none of these studies measured visual and haptic orientation matching errors within the same experimental settings. Chapter 3 describes a set of experiments in which we asked participants to haptically and visually match the orientation of a visually presented stimulus (a computer projected line) at different positions of workspace. Although the variable errors were larger for haptic matching, the systematic errors did not differ for the two modalities. Because the systematic errors reflect the structures of visual and haptic space, we could conclude that visual and haptic space have the same structure. The equality of the structure of visual and haptic space could be due
Figure 1.7: Illustration of a method to obtain a direct measurement of the curvature of visual space. By means of the remote control the arrow (1) is rotated such that it seems to be pointing at the sphere (2). In successive trials different positions of the arrow and the sphere are used.

to visualization during haptic matching. However, participants who have been blind from birth show similar haptic matching errors as blind-folded sighted participants (Zuidhoek, Noordzij, Kappers, & Postma, submitted), suggesting that structure of haptic space is not a derivative of the structure of visual space.

1.5 Task dependence of haptic space

In a subsequent set of experiments, described in Chapter 4, we investigated the structure of haptic fronto-parallel space. This research was performed in collaboration with researchers from the Physics of Man department in Utrecht. We decided to investigate the structure of frontal space to extend the studies of haptic space for the other two body related planes (horizontal and sagittal). The three planes orthogonal with respect to the body are shown in Figure 1.9. Systematic haptic orientation matching errors were found for the horizontal and sagittal plane. We investigated whether similar errors could be found for the frontal plane and whether these errors depended
Figure 1.8: Possible results of a direct curvature measurement of visual space. Triangle 1 denotes negative, triangle 2 zero, and triangle 3 positive curvature.

on the task used. For a task in which participants matched the orientation of two bars large systematic errors in the frontal plane were found. Errors for bar positions above the shoulders were smaller than those for bars presented near the waist. As for the horizontal plane, female participants made larger errors than male participants. This difference between the performance of female and male participants was first discovered by Kappers (2003). Van Mier and colleagues followed up on this work (Van Mier, Blommaert, & Kappers, 2003). They were able to demonstrate that the difference in haptic matching performance between female and male participants already exists for children as young as six years old.

Two different haptic orientation tasks showed that the large systematic errors were task specific. When participants were asked to set the bars in a particular orientation (for example, 45 degrees with respect to the horizontal), they made much smaller errors than those observed in the matching task. Also when participants were asked to verbally report the orientation of a haptically presented bar they made very small errors compared to those of the matching task. These findings lead to the conclusion that the structure of haptic space is task dependent. The task dependence of the haptic space can be explained by assuming two internal reference frames: One resembling the external reference frame, and one egocentric frame, related to arm and hand orientation. In the haptic matching task participants rely on the egocentric
frame to a large extent. In the production and perception task more weight is given to the external reference frame.

1.6 Intercepting oriented objects

Chapter 5 presents an experiment in which we investigated the structure of visual frontal space in more detail. In an additional experiment we looked at the effect of the incorrect orientation perception on interception movements. To investigate the structure of frontal visual space we varied the distance between the reference stimulus and the matching stimulus. The matching errors increased as the distance between the two stimuli increased. The pattern of results suggested that the errors were caused in part by perspective distortions. Participants could only in part correct for the effect of perspective on the retinal image. For the interception task we projected a line on a large computer screen which moved towards the participant. On its way to the participant the line became invisible. Participants were asked to intercept the invisible line by pressing a bar on the screen at an interception point, such that the bar would cover the line. The orientation of the bar at the interception point reflected the misperceived orientation of the line during the part of its movement in which it was still visible. Participants could not accurately match the orientation of the line at the interception point. The size of the matching errors corresponded to a perceived line orientation at a position farther away than the disappearance point.
1.7 Conclusion and outlook

The studies reported in this thesis shed some light on how human perception and motor planning interact in the planning of grasping movements towards oriented objects. More research is needed to gain a better understanding of how grasping movements are planned. An important aspect of this research will be the effects of task requirements.

In addition, more research will be needed to extend current models to grasping movements and obstacle avoidance. Possibly new models need to be developed to accurately describe human movement control. Such a model might incorporate a constraint hierarchy in which the order of the constraints depends on the task requirements.
Chapter 2

Posture-based or trajectory-based movement planning? A comparison of direct and indirect pointing movements

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2.1 Introduction

Various models have been proposed to explain the planning and execution of arm movements (Feldman & Levin, 1995; Gielen et al., 1997; Harris & Wolpert, 1998; Soechting et al., 1995; Rosenbaum et al., 1995, 2001; Uno, Kawato, & Suzuki, 1989). These models can be classified into two categories. The first category, which we will refer to as ‘posture-based’, assumes that a final posture is selected for each target position of the finger tip. Examples of models within the posture-based category are Donders’ law (Von Helmholtz, 1867) and the equilibrium point hypothesis (Feldman & Levin, 1995). Donders’ law predicts that the final posture does not depend on the initial posture. Models within the second category, which we will refer to as ‘trajectory-based’, use a criterion according to which an optimal trajectory towards the final finger position is selected based on the initial posture and the final finger position out of many possible trajectories. The final posture of the arm results from the selected trajectory. Examples of models within the trajectory-based category are the minimum work model (Soechting et al., 1995), the minimum torque-change model (Uno et al., 1989), and the minimum-variance model (Harris & Wolpert, 1998). The knowledge model of Rosenbaum et al., (1995, 2001) is a special case within this classification scheme. In the knowledge model a final posture is selected before movement execution, which would make the model posture-based. However, this final posture is selected both on the basis of a spatial and a travel-cost criterion, making the model trajectory-based. This means that the model incorporates aspects of both planning strategies.

Several studies have tried to discriminate between models to account for observed movement data. Soechting et al. (1995) compared the predictions of Donders’ law and the minimum-work hypothesis with experimental data. In their study participants were instructed to point towards targets starting from different positions in 3-D space. An effect of starting position on the posture of the arm at the end of the pointing movement was found, which argues against Donders’ law. Gielen et al. (1997) replicated this result. Additional evidence against Donders’ law was found by Desmurget et al. (1998) who instructed participants to grasp a cylinder while initiating their movements from different starting postures. The initial posture at the beginning of the movement was found to affect the posture of the arm at the end of the movement. An additional comparison between Donders’ law and the minimum work hypothesis was performed by Vetter, Flash, and Wolpert (2002) who asked participants to touch a target bar using a hand-held virtual stick.
Predictions for the relative amounts of upper arm and forearm torsion of the two models were compared with the measured torsion. A small but significant violation of Donders’ law was found. However, the data could not be explained by the minimum work model either, which predicted much larger effects of starting position on the final arm posture than observed.

In a series of experiments Desmurget and colleagues (Desmurget et al., 1995, 1998; Grea, Desmurget, & Prablanc, 2000) tried to discriminate between posture-based and trajectory-based models by investigating the effect of a change in target position or target orientation at movement onset on the final arm posture. Desmurget et al. (1995) asked participants to grasp a bar. In a proportion of the trials the orientation of this bar was changed at movement onset. A similar task was used by Desmurget, Grea, and Prablanc (1998) who asked participants to grasp a bar from different initial positions. In this study the orientation of the bar could change at movement onset. Grea, Desmurget, Prablanc (2000) asked participants grasp a sphere. In some of the trials the position of the sphere changed at movement onset. By changing the target’s position or the target’s orientation at movement onset, the observed movement trajectories changed with respect to those in unperturbed movements. However, changes in position or orientation did not affect the posture of the arm at the end of the movement. This result argues in favor of posture-based models, like Donders’ law. In the study by Desmurget et al. (1998) the initial posture of the arm was found to affect the posture of the arm at the end of the movement, which argues against Donders’ law.

The studies carried out up to now could not decisively discriminate between trajectory-based and posture-based planning, nor did they provide compelling evidence in favor of one of the specific models for movement execution, thereby rejecting others. Several studies presented evidence against Donders’ law (Soechting et al., 1995; Gielen et al., 1997; Desmurget et al., 1998; Vetter et al., 2002), but other studies could not reject this law (Desmurget et al., 1995, 1998; Grea et al., 2000). The results by Vetter et al. (2002) present evidence against Donders’ law, but the violations of this law are very small and could not be predicted by the minimum work model either. Moreover, few studies tested the minimum torque-change hypothesis extensively for movements in 3-D. However, there is good evidence that the minimum commanded-torque-change model or the angular-jerk model might provide better predictions of experimental data than the minimum torque-change model (Wada, Kaneko, Nakano, Osu, & Kawato, 2001). Following our definition of posture-based and trajectory-based models, the best way to discrim-
In this study we tried to discriminate between various models (trajectory-based or posture-based) by asking participants to make point-to-point arm movements to targets in 3-D via different trajectories. In half of the trials participants were asked to move directly to a target, starting from various positions, while in the other half of the trials they were asked to move to the target position from the same starting positions by a so-called via-point. Donders' law was considered as the null-hypothesis that begin position and movement path do not affect final posture.

In general arm movements are expected to be smooth, to require little energy, and to avoid extreme joint torques. Therefore, a detailed comparison of the predictions of the various models will be necessary to determine which, if any, criterion is used in human movement planning. For such a detailed comparison of the different models we added two additional conditions to our experiment. First, we varied the velocity at which participants were asked to move from one target to another, thereby trying to replicate the results of a study by Nishikawa, Murray, and Flanders (1999). In their study no effect of movement velocity on final posture was found, which is consistent with predictions by the minimum work model and by Donders’ law. An effect of movement velocity on the final posture would be consistent with predictions by the knowledge model, due to the optimal movement time included in the travel cost criterion used in the model (Rosenbaum et al., 1995). In addition to variations in the path towards the target position, in starting position, and in movement velocity, we attached a weight to the forearm of the participant in one of the conditions. The data of this condition were compared with the data without such a weight. The minimum work and the minimum torque-change model predict an effect of load on the final posture, whereas posture-based models, such as Donders’ law, do not predict an effect.
2.2 Method

2.2.1 Experiment

Participants

In each experimental condition 10 participants took part. Nine participants took part in all conditions. One participant dropped out after the pointing task with and without a weight attached to the arm. Another participant replaced this subject for the fast and slow pointing movements tasks. The age of the participants ranged from 16 to 56 (mean age of 31, standard deviation of 12.3). Two participants were left-handed. These left-handed participants were asked to perform the pointing movements with their right hand, like the other participants. On inspection of their movement data (average change in upper arm torsion, movements paths) no obvious differences were found with the data of the right-handed participants. Five participants, who were not members of the department, were paid for their participation. None of the participants had any known history of sensory or motor disorders. Before the start of the experiment subjects were informed about the experimental protocol, which was approved by the Medical Ethical Committee of the University of Nijmegen. All participants gave their informed consent for their participation in the experiment. The participation by the 16 years old subject was approved by his parents.

Apparatus

During the pointing task participants were seated in a chair. A Philips 4750 LCD projector was used to project the stimuli on a 2.5 by 2 meter vertical projection screen. Stimuli were presented within a 115 by 86 cm display image on the vertical screen. The presentation of the stimuli was controlled by a PC. During the experiment the orientation of the upper arm and the forearm of the participant was measured using two bracelets each with 14 infra-red light-emitting diodes (IREDS). Ten of the IREDS were distributed equally across the bracelet in a zigzag pattern which consisted of two rings with 5 IREDS each with a distance of 4 cm between the two rings. The remaining 4 IREDS were attached to the edges of a cross of 5 cm in diameter attached to the bracelet. The location of the IREDS was recorded using an Optotrak 3020 system. Using the programs Rigmaker and Rigid provided with the Optotrak system the orientation and location of each bracelet was determined. The orientation of each bracelet could be measured with an
accuracy better than 0.5 degrees.

In one of the conditions a weight of 0.6 kg was attached symmetrically around the wrist of the participant, at a distance of about 28 cm from the elbow.

Stimuli

Stimuli consisted of red and green filled circles with a diameter of 6 cm projected on the projection screen by the LCD projector. Red circles represented final target locations. The green circles represented the via points.

The positions of the stimuli with respect to the participant are illustrated in Figure 2.1. Each of the stimuli could serve as a target or a via point. All stimuli were presented within a distance of 80 cm from the shoulder. Panel A of Figure 2.1 shows a top view of the participant and the screen. Participants were facing the projection screen under an angle to allow them to point comfortably to the upper left stimulus. Panel B shows the positions of the stimuli on the screen. Using the Optotrak system the locations of the stimuli were measured with respect to a coordinate system centered at the right shoulder. The horizontal axis of this coordinate system was chosen to pass through both shoulders. The other axes were orthogonal to the horizontal axis. One axis was oriented upwards and one straight forward relative to the subject. The center circle was presented at coordinates (51, -15, 17), where the first coordinate represents the depth, the second coordinate the horizontal distance, and the third coordinate the vertical distance. The upper left circle was presented at (63, 38, 30), the upper right circle coordinates were (39, -36, 29), and the bottom circle was presented at (52, -19, -11). All distances were measured in cm. Because most circles were presented closer to the shoulder than the length of the outstretched arm (the upper left circle could just be reached by the participants), participants bent their arms during their arm movements. At the end of each movement they touched the target with their finger.

The orientation of upper arm and forearm at each target was expressed as a rotation vector (in degrees) (Haslwanter, 1995) from the mean posture adopted by the participant while pointing to the center target.

Design

Participants performed pointing movements in each of four conditions: (1) ‘No weight’ and without an instruction on movement speed, (2) ‘weight’, with a weight of 0.6 kg attached to the forearm, (no instruction of movement
Figure 2.1: The position of the stimuli in the experiment. The stimuli were projected on projection screen which participants viewed under an angle (Panel A). The projected stimuli were organized in a triangle with respect to each other, with the reference stimulus in the center (Panel B).

speed) (3) ‘fast’, where participants were asked to move fast from target to target, resulting in an average movement time of 0.73 s (SD = 0.086 s), and
(4) ‘slow’, in which participants were asked to move slowly from one target to the other, trying to arrive at the target location when the next target was presented, resulting in an average movement time of 1.3 s (SD = 0.18 s). In the ‘fast’ condition the inter-trial time was set to 1.5 seconds. In the ‘no weight’ and ‘weight’ conditions the inter-trial time was 2 seconds, while in the ‘slow’ condition an inter-trial time of 2.5 seconds was used.

The four conditions were presented in four separate blocks. The ‘no weight’ and the ‘weight’ conditions were presented in one session, and the ‘slow’ and the ‘fast’ condition were presented in another session. The order of the sessions and the order of the conditions within the sessions were randomized across participants.

Within each condition 8 blocks with 25 trials each were presented. At the first trial of each block the central target was presented. The posture of the arm when pointing to this target was used to determine the reference posture. The second trial moved the participant’s finger from the center target to one of the outer targets in a direct movement. The first two trials of each block were followed by a random sequence of direct and indirect movements. For each new trial the next target was selected at random. Also, direct and indirect movements were selected at random for each new trial.

Procedures

At the beginning of the experiment participants were seated in a chair. The right shoulder was fixated by means of a diagonal seat belt. Participants were told they would be presented with green and red circles on the projection screen. Their task was to point to the red target, moving their finger via the green target. They were asked to keep pointing to the red target until the next set of circles appeared on the screen accompanied by a computer beep. If the new green circle appeared at the location of the red circle of the previous trial (the new green circle then appeared under the finger tip of the participant) they were instructed to point to the red circle directly. To become acquainted with the task participants received practice trials until they could carry out the task correctly.

2.2.2 Model simulations

In order to quantitatively compare experimental data and model predictions we simulated arm movements for three trajectory-based criteria: (1) the minimum work criterion, (2) the minimum angular jerk criterion, and (3) a
minimum travel cost criterion. Moreover, the results were compared with the null-hypothesis (Donders’ law), that final posture does not depend on previous postures, on movement velocity, or on the load attached to the forearm. We did not simulate arm movements predicted by the minimum torque-change criterion, since convergence to the optimal movement trajectory was sometimes hard to obtain. In addition, Wada et al. (2001) showed that the minimum commanded torque-change model gave more accurate predictions than the minimum torque-change model and that minimum angular jerk simulations can be used as a good approximation to the predictions by the minimum commanded torque-change model.

The amount of peak work, \( W \), during an arm movement can be computed using the following equation:

\[
W = \frac{1}{2}(I_1(\ddot{\eta}^2 \sin^2 \theta + \dot{\theta}^2) + I_2(\dot{\eta} \cos \theta + \dot{\zeta})^2 + I_3(\Omega_y^2 \cos^2 \phi + \Omega_z^2 \sin^2 \phi + 2\phi \Omega_z + 2\Omega_z \Omega_y \cos \phi \sin \phi) + I_4(\Omega_y^2 \sin^2 \phi + \Omega_z^2 \cos^2 \phi - 2\Omega_z \Omega_y \cos \phi \sin \phi) + 2A(\Omega_y \cos \phi + \Omega_z \Omega_y \sin \phi + \dot{\phi} \Omega_z \cos \phi))
\]

Here \( \phi \) represents the elbow flexion angle (\( \phi = 0 \) corresponding to full extension), \( \eta \) and \( \theta \) represent the yaw and elevation angles at the shoulder respectively, and \( \zeta \) represents the upper arm torsion. For a more detailed definition of these joint angles, of the inertia constants \( I_1, I_2, I_3, I_4 \), and the angular velocities \( \Omega_x, \Omega_y, \Omega_z \), see Soechting et al. (1995). Like Soechting et al. (1995) the optimal trajectory was selected as the trajectory with minimum work halfway through the trajectory.

The minimum angular jerk criterion (see Wada et al., 2001) minimizes the function:

\[
C_{AJ} = \frac{1}{2} \int_0^{t_f} \sum_{i=1}^4 \left( \frac{d^3 \theta_i}{dt^3} \right)^2 dt
\]

where the \( \theta_i \) represent the joint angles (flexion/extension of the elbow, and three orthogonal rotation axes at the shoulder). The integration is over the time interval between movement onset (\( t = 0 \)) and movement offset (\( t = t_f \)). The path in joint space according to this criterion is a fifth order spline.

The minimum travel cost criterion is used in the model of Rosenbaum and colleagues (1995, 2001). The model assumes that the final posture of a movement is determined by comparing all postures stored in memory. The stored posture, which best fits a set of constraints, is selected. An important constraint is a small travel cost. After the best stored posture is selected
a grid search is performed around the stored posture, until the end of the available planning time is reached. If the time to plan the movement is unrestricted, a grid search over the entire posture space is performed. In this case the optimal solution does not depend on the set of stored postures. To compare the predictions of the knowledge model with the predictions of the other models, we assume that postures are based on the low travel cost constraint only, and that planning time is unrestricted. With these assumptions the entire space of possible end postures is searched for the posture with the minimal travel cost. The travel cost is computed by the following equation:

\[
V_p = \sum_{j=1}^{4} \left( \frac{k_j \alpha_j}{r} \left( 1 + [T_j - k_j \ln(\alpha_j + 1)]^2 \right) \right)
\]

where the \( \alpha_j \)'s denote the changes in the joint angles for each of the 4 degrees of freedom (three in the shoulder, one in the elbow). \( k_j \)'s are constants related to the joint stiffness. We set these constants equal to 1 (see Rosenbaum et al., 2001).

For each of the models (minimum work, minimum travel cost, minimum angular jerk) the minimum value of the cost function was found by a grid search. That is, we varied the torsion angle, \( \zeta \), from −180 degrees to 180 degrees in steps of 1 degree, and computed the other three angles (denoted \( \eta \), \( \theta \), and \( \phi \) using the fact that the finger is at the starting position and the target position at the begin and end of the movement, respectively), taking into account the normal physiological movement range of the joints. The elbow angle \( \phi \) can be computed from the distance towards the target. The shoulder angles \( \eta \) and \( \theta \) were found by means of a simplex search. For all values of the upper arm torsion, \( \zeta \), we determined the corresponding value of the cost function.

For the comparison of the data for the ‘no weight’ condition with the model predictions we used a movement duration of 1 second. For the starting posture of each simulated movement, we used the mean observed posture of the arm corresponding to that starting position.

### 2.3 Results

Figures 2.2 and 2.3 show the mean torsion of the upper arm and the forearm, respectively, at the three targets without instructions regarding movement speed (‘no weight’) and with a weight attached to the subject’s wrist.
(‘weight’). Torsion was defined as the angle of rotation along the longer axis of the upper arm or forearm with respect to the average orientation while pointing to the center target. Bars indicate the mean torsion across subjects. Lines on top of the bars represent the 95% confidence intervals across participants.

Figure 2.2: Mean torsion (in degrees) of the upper arm across participants in the ‘no weight’ condition and the ‘weight’ condition. The lines on top of the bars show the size of the 95% confidence interval. The solid and the open bars refer to direct and ‘via’ movements respectively. Numbers along the horizontal axis refer to starting position for direct and indirect movements to the target.

A repeated measures analysis of variance tested the effects of starting position, weight attached to the forearm, and path (direct movement or a movement along a via point) for each of the three targets. This analysis provides a direct test of Donders’ law, since the law predicts no effects of starting position, path towards the goal position, and the weight attached to the forearm on the final posture of the arm.

Small, but significant effects were found of the path towards the target position and of starting position on both forearm and upper arm torsion for
Figure 2.3: Mean torsion (in degrees) of the forearm across participants in the ‘no weight’ condition and the ‘weight’ condition. The lines on top of the bars show the size of the 95% confidence interval. The solid and the open bars refer to direct and ‘via’ movements, respectively. Numbers along the horizontal axis refer to starting position for direct and indirect movements to the target.

all three targets. The size of these effects was typically a few degrees. No significant effects were found of the weight attached to the forearm.

Specifically, for the bottom target a significant interaction effect was found of path and starting position on the mean torsion of the upper arm ($F(1, 9) = 5.567, p = 0.043$). On forearm torsion the main effect of path was significant ($F(1, 9) = 5.612, p = 0.042$). For the upper right target a significant path-by-starting-position interaction was found on upper arm torsion ($F(1, 9) = 12.951, p = 0.006$). The only significant effect on forearm torsion was a main effect of path ($F(1, 9) = 7.315, p = 0.024$). For the upper left target both main effects of path ($F(1, 9) = 20.713, p = 0.001$) and starting position ($F(1, 9) = 30.437, p < 0.001$) were significant.

Figures 2.4 and 2.5 show the mean torsion of upper arm and forearm for
the two speed conditions. In an analysis of variance the effects of movement speed, starting position, and path towards the target position were tested. Small, but significant effects of starting position and path towards the target position were found for all targets both on forearm and upper arm torsion for both movement velocities. For the two upper targets interaction effects of starting position and velocity, and of path and velocity were found.

In more detail, significant path by starting position interaction effects on upper arm torsion \((F(1, 9) = 6.621, p = 0.030)\) and forearm torsion \((F(1, 9) = 6.831, p = 0.028)\) were found for the bottom target. For the upper right target there was a significant path-by-starting-position interaction effect on upper arm torsion \((F(1, 9) = 8.146, p = 0.019)\). On forearm torsion there was a significant path-by-velocity interaction effect \((F(1, 9) = 9.005, p = 0.015)\). The two main effects of path \((F(1, 9) = 6.970, p = 0.027)\) and starting position \((F(1, 9) = 11.126, p = 0.009)\) on forearm torsion were significant. The upper left target showed a significant velocity-by-starting position interaction on upper arm torsion \((F(1, 9) = 5.699, p = 0.041)\). Significant main effects of starting position \((F = 7.897, p = 0.020)\) and path \((F(1, 9) = 5.713, p = 0.041)\) were found. On forearm position there was a significant velocity-by-starting position interaction \((F(1, 9) = 12.552, p = 0.006)\) and a significant main effect of path \((F(1, 9) = 8.432, p = 0.017)\).

### 2.3.1 Model simulations

As described in the method section we compared predictions by the minimum work model, the minimum angular jerk model, and the minimum travel cost model regarding the effects of starting position, and the path taken towards the target position. These predictions were compared with the null hypothesis (Donders’ law) that starting position and the path taken towards the target position do not affect final posture. Figure 2.6 shows predicted and observed effects of starting position for direct movements (i.e., no via-point) on arm torsion at the end of the movement. The plot shows that the minimum work model, the minimum angular jerk model, and the minimum travel cost model predict larger effects of starting position on the final posture of the arm than actually observed. The absolute errors between model predictions and observed data were considerably smaller for the minimum angular jerk model and the minimum travel cost model than for the minimum work model. Statistical tests showed that also the null hypothesis was violated. In terms of absolute errors the null hypothesis (Donders’ law) still gave the best description of the data.
Figure 2.4: Mean torsion (in degrees) of the upper arm across participants in slow speed and fast speed conditions. The lines on top of the bars show the size of the 95% confidence interval. The solid and the open bars refer to direct and ‘via’ movements respectively. Numbers along the horizontal axis refer to starting position for direct and indirect movements to the target.

Figure 2.7 shows the predictions of the models and the observed effects of movements along a via-point towards the target position on the torsion of the arm at the end of the movement. The minimum work model shows large over-estimations of the effect of the path towards the target. The minimum angular jerk model and the minimum travel cost model gave a better fit of the observed data. Minimum travel cost and Donders’ law gave the best predictions of the data.

2.4 Discussion

Table 2.1 presents an overview of the experimental results obtained in this study, and of results obtained by previous studies. Moreover, it shows the predictions by various models. In the table we included qualitative predictions
Figure 2.5: Mean torsion (in degrees) of the forearm across participants in slow speed and fast speed conditions. The lines on top of the bars show the size of the 95% confidence interval. The solid and the open bars refer to direct and ‘via’ movements respectively. Numbers along the horizontal axis refer to starting position for direct and indirect movements to the target.

of Donders’ law (Von Helmholtz, 1867), the equilibrium point (EP) hypothesis (Feldman & Levin, 1995), the minimum angular jerk model (Wada et al., 2001), the minimum torque-change model (Uno et al., 1989), the minimum work model (Soechting et al., 1995), the minimum variance model (Harris & Wolpert, 1998), and the knowledge model (Rosenbaum et al., 1995).

For the EP hypothesis it is hard to make reliable predictions for all conditions. At the muscle level and the joint level the predictions by the EP hypothesis have been clearly spelled out. However, this is not the case for multi-joint movements. The only report regarding the extension of the EP hypothesis to multi-joint movements is the study by Lestienne, et al. (2000). However, this study does not allow to extend this hypothesis to complex movements, such as the four degrees of freedom arm movements in our study. Two predictions for the EP hypothesis can be made for our data set: The final arm posture will neither depend on the movement velocity, nor on the
Figure 2.6: Predicted and observed effects of starting position on the torsion of the arm at the end of the movement for direct movements from two different start positions for each target. For each target position the difference (in degrees) between the torsion at the end of the movement for the two starting positions is shown. This implies that the panel for target 1 shows the difference in upper arm orientation to target 1, starting from targets 2 and 3. MW, MAJ, and MTC refer to the predictions of the minimum work model, the minimum angular jerk model, and the minimum travel cost model, respectively. Obs refers to the observed effects. The vertical lines on top of the bars for the observed data show the 95% confidence interval. The asterisks near the bars of the predicted values show the results of t-tests testing whether the predicted mean was significantly different from the observed mean. A triple asterisk denotes a significant deviation at the $p < 0.001$ level.

It is well known that rotations in 3-D do not commute (see e.g., Tweed & Vilis, 1987). Therefore, the orientation of the arm after two single-axis rotations depends on the order of the rotations. As a consequence, the orientation of the fully extended arm after a single-axis rotation in the shoulder along the shortest path starting from a particular posture to a target will differ from the orientation of the arm after two single-axis rotations along the shortest path from the same initial posture to the same target by a via-point (see Stoker, 1969). As a consequence, all models, which predict single-axis rotations along a shortest path for the fully extended arm (such as the minimum
Figure 2.7: Predicted and observed effects of path towards the target position on the torsion of the arm at the end of the movement. For each target position and each starting position the difference (in degrees) between the torsion at the end of the movement for the direct and the ‘via’ movement is shown. MW, MAJ, and MTC refer to the prediction for the minimum work model, the minimum angular jerk model, and the minimum travel cost model, respectively. Obs refers to the observed effects. The small vertical lines on top of the bars for the observed data show the 95% confidence interval. Numbers along the horizontal axis refer to starting position for direct and indirect movements to the target. The asterisks near the bars of the predicted values show the results of t-tests testing whether the predicted mean was significantly different from the observed mean. A single asterisk represents a significant deviation at the $p < 0.05$ level. Double and triple asterisks denote significant deviations at the $p < 0.01$ and $p < 0.001$ level respectively.

angular jerk model, the minimum work model, the minimum torque-change model, and the minimum variance model), will predict an effect of starting position and of the path towards the goal (direct movement or through a via-point). For similar reasons these models also predict an effect of starting position and path towards the goal for arm movements with elbow flexion.

The equations for minimum angular jerk and minimum travel cost (part of the knowledge model) depend on the movement time. It can be shown that the minimum work model does not predict an effect of movement time (Nishikawa et al., 1999). The angular jerk model and the knowledge model
Table 2.1: Summary of experimental results and model predictions. The table lists the effects of starting position, path towards the goal, movement speed and weight attached to the forearm on the posture of the arm at the end of the movement. A question mark indicates that no specific predictions are made by the model, or that the simulations results of the model are unknown.

<table>
<thead>
<tr>
<th>Effect of starting position</th>
<th>Effect of path to goal</th>
<th>Effect of movement velocity</th>
<th>Effect of inertia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Soechting et al., 1995</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gielen et al., 1997</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desmurget et al., 1998</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desmurget et al., 1995</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Flanders et al., 2003</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Fischer et al., 1997</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Donders’ law</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>EP Hypothesis</td>
<td>?</td>
<td>?</td>
<td>No</td>
</tr>
<tr>
<td>Minimum angular jerk</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Minimum torque-change</td>
<td>Yes</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Minimum work</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Minimum variance</td>
<td>Yes</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Knowledge model</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
predict small effects of movement velocity on the final posture of the arm.

Because the inertia of the arm plays an important role both for the minimum work model and the minimum torque-change model, these models predict that the final posture of the arm depends on the weight of the forearm. The equations of minimum angular jerk, and minimum travel cost do not depend on the weight attached to the arm segments, and therefore predict no effect of the weight of the forearm.

Our study replicated the effects of starting position on the final arm posture reported in previous studies (Desmurget et al., 1998; Gielen et al., 1997; Soechting et al., 1995). All studies, which have tested the effect of starting position, have reported an effect of starting position. These observations argue against Donders’ law which predicts a unique posture of the arm for each position of the finger in 3-D space, independent of previous postures. Simulations with the minimum work model, the minimum angular jerk model, and the minimum travel cost model show that these three models predict larger effects of starting position than actually observed. The observation, that the minimum work model predicts larger effect of starting position than observed, corresponds to earlier reports by Vetter, Flash, and Wolpert (2002), and by Klein Breteler, Hondzinski, and Flanders (2003). For our data set, the minimum work model not only predicts too large effects, also the direction of the effects is not correctly predicted.

In the present study, small but significant effects were found of the path taken towards the target position on the posture of the arm at the end of the movement. These effects relate to previous findings by Desmurget and colleagues (Desmurget et al., 1995; Desmurget & Prablanc, 1997; Greart et al., 2000), where a change of the target position or orientation after movement onset resulted in a different path to the target for perturbed and unperturbed trials. In their study no effect of a target change was found on the posture of the arm at the end of the movement. This result may seem contradictory to the results in our study. However, this discrepancy can be resolved if we consider the size of the effect. In the studies by Desmurget and colleagues the change in target position led to relatively small differences in movement trajectory. The differences in path were much smaller than the differences in path for the direct movements and for movements along a via-point in our study, where the effects of path were small. Therefore, we speculate that any effects of path in the study by Desmurget were too small to be observed in their study.

No effects of movement velocity were found, which is in agreement by earlier findings by Nishikawa et al. (1999), but at odds with findings by
Fischer, Rosenbaum, and Vaughan (1997). However, Fischer et al. (1997) used rhythmic repeated movements, which have properties that differ from those of discrete movements (Schaal, Sternad, Osu, & Kawato, 2001).

We did not find an effect of the weight attached to the forearm on the posture of the arm at the end of the movement in this study. In a previous study Flanders, Hondzinski, Soechting, and Jackson (2003) reported an effect of a rod with a weight of 0.46 kg attached to the upper arm on the initial posture. A possible explanation for the different results might be that subjects are used to making movements with objects of different weights at their hand, which basically corresponds to the situation with the weight at the wrist in our study. Flanders et al. (2003) attached a weight to the upper arm some distance away from the long axis through the upper arm. In their study the weight was attached to the upper arm because simulations suggested that more conventional weights (such as the weight symmetrically distributed around the wrist) would not significantly alter the mass distribution and therefore the predictions of the minimum work model. To investigate whether the absence of a significant effect of the weight attached to the forearm found in our study provides evidence against the minimum work model, we did some additional simulations with the model. These simulations showed that the predicted effect of the weight attached to the wrist was on the order of a few degrees. Since the effect found in our study was on the same order, it may have been too small to reach significance.

In our experiment participants quickly adapted to the weight attached to the wrist, typically within a few trials. Previous research by Shadmehr and Mussa-Ivaldi (1994) investigated the adaptation to more complex changes of the arm dynamics. In their study participants adapted to a force applied to the hand during reaching movements. In the first few trials the force applied to the hand strongly affected the hand trajectories. After some practice hand paths became smoother and resembled those of reaching movements without a force applied to the hand. If participants moved according to a minimum work or a minimum torque-change strategy such an adaptation would not take place.

To conclude, none of the models considered could fully account for the data observed. Our study indicates that future tests of models for motor control (1) should compare the predictions of several models for a single, large data set, (2) and that the comparison should include movements in 3-D, rather than in 2-D.
Chapter 3

Visual and haptic matching of perceived orientations of lines²

3.1 Introduction

One of the first processing steps needed for grasping an object in the visual world is perceiving its size and orientation. In this context, it is important to notice that many studies have shown that object properties are not always perceived correctly. Several differences have been reported between world space and the representation of this space in the brain. For example, parallel lines in world space are not always perceived as parallel lines (Cuijpers, Kappers, & Koenderink, 2000; Kappers & Te Pas, 2001) and objects presented at the same distance but at a different viewing angle often do not look equidistant (see, e.g., Foley, 1980). Moreover, angles between two lines are found to be perceived incorrectly (Chen & Levi, 1996; MacRae & Loh, 1981; Regan, Gray, & Hamstra, 1996) and, related to this observation, the angles of a triangle constructed by arrows pointing towards the perceived vertices of the triangle do not sum to 180 degrees (Koenderink et al., 2000). Finally, the estimation of the length of a line depends on whether the line is on a flat or a curved surface (Norman, Todd, Perotti, & Tittle, 1996; Norman, Lappin, & Norman, 2000).

Soechting and Flanders (Flanders & Soechting, 1995; Soechting & Flanders, 1993) investigated whether the differences between the actual orientation of objects and the perceived orientation affect manual matching of orientations of objects. In their experiments participants were asked to match a visually or verbally presented 3D orientation with a bar at different locations in space. Systematic errors were made by participants carrying out this task. In another study Kappers and Koenderink (1999) found systematic errors when participants were asked to match the orientation of a haptically perceived bar with that of a test bar at various places in the horizontal plane.

These results have raised the question whether errors in the percept of visually and haptically presented bars are similar and to what extent errors in visual perception of the orientation of a bar affect haptic matching of the orientation. A first attempt to address this question was presented by Cuijpers in his doctoral thesis (Cuijpers, 2000), where he compared the results of a visual (Cuijpers et al., 2000) and a haptic matching task (Kappers, 1999). Cuijpers (Cuijpers, 2000) showed that the structure of visual and haptic space is qualitatively similar but quantitatively different. However, the experimental conditions for the haptic and visual matching were different, leaving open the option that the quantitative differences could be due to differences in the experimental setup of the two matching experiments. In the experiment by Cuijpers et al. (Cuijpers et al., 2000) the two bars
were presented in a horizontal plane at eye height while in the experiment by Kappers and Koenderink (Kappers & Koenderink, 1999) the stimuli were presented on a table at waist level. In addition, the distance between stimuli differed across experiments. The aim of the present study was to investigate whether errors in visual and haptic matching of line orientations are quantitatively similar. To allow for a quantitative comparison across modalities we asked participants to match visually presented orientations both visually and haptically in the same experimental conditions.

Three experiments were carried out. In the first experiment participants were asked to visually match the orientation of two lines. Both lines were presented on a large screen which participants looked at from aside. By the choice of the stimulus locations the influence of viewing angle and distance was tested. Based on results by Cuijpers et al (Cuijpers et al., 2000) and Kappers and Koenderink (Kappers & Koenderink, 1999) viewing angle was expected to have an effect, but no effect was expected of viewing distance.

The second experiment involved haptic matching with visual feedback. Participants were presented with the same visual stimulus as in the first experiment. They were asked to match its orientation by holding a bar in the same orientation at one of three different positions. While matching the orientation the reference line remained visible and the orientation of the bar could be inspected visually. This makes the experiment different from the experiments by Soechting and Flanders (Soechting & Flanders, 1993) where either the stimulus or the bar could not be seen while matching.

In the third experiment visual information was eliminated during haptic matching of the reference orientation. This was done to exclude a possible dominant contribution of visual perception to the matching of the bar’s orientation in Experiment 2. If the use of visual information dominated that of haptic information and if errors in visual and haptic matching differ, a different pattern of results has to be expected for haptic matching with (experiment 2) and without (experiment 3) visual feedback.

3.2 Experiment 1

In the first experiment the perceived orientation of visually presented lines in the vertical plane was investigated when participants looked at the stimuli from aside. Two viewing positions were used: One to the left of the stimuli and one to the right. In the experiment participants were presented with two lines on a large screen, and they were asked to match the orientation
of one line (the ‘matching line’) with the orientation of the other line (the ‘reference line’). They did this by adjusting the orientation of the matching line using a remote control until they thought it matched the orientation of the reference line.

3.2.1 Method

Participants
The stimulus lines were matched from two viewing positions. Six participants matched the stimuli from the left and seven from the right. Three participants took part in both matching situations. Two of the three were the authors. All other participants were naive with respect to the purpose of the experiment. Six of the participants (not members of the department) were paid for their participation. All participants had normal or corrected-to-normal vision.

Apparatus
A LCD projector (Philips 4750) connected to a Pentium PC (166 MHz) was used for the presentation of the stimuli. Two lines were projected within a 142 times 105 cm computer display image on a 2.5 by 2 meters projection screen. The resolution of the projected screen was 640 by 480 pixels. The orientation of one of the projected lines could be adjusted using a computer keyboard in steps of 2, 0.5, or 0.1 degrees.

Stimuli
The stimuli consisted of computer-generated lines. Each line consisted of seven dots each at 13 mm distance within the 142 by 105 cm display image. Seven dots were used instead of a solid line, since a solid line would allow participants to estimate its orientation by looking at the staircase pattern of the dots within the line which originated from the finite resolution of the visual display in graphics mode. The seven dots of each line were plotted in white on a black background. The reference line was presented in the upper right part of the screen for both viewing conditions (from the left and the right), with its center at 122 cm from the left and 13 cm from the top of the display image. The matching line was presented with its center in the upper left part of the image (13 cm, 13 cm), in the middle upper part of the image (40 cm, 13 cm), or in the middle lower part of the image (40 cm, 40 cm).
Figure 3.1 shows a top view of the location of the stimuli and their location with respect to the participant. The centers of the matching line locations are indicated by an asterisk, the center of the reference line location by a plus sign.

![Top view diagram](image)

**Figure 3.1**: Top view of the location of the stimuli with respect to the viewing positions of the participants. Dashed lines indicate edges of computer generated display. Asterisks denote the centers of the matching line locations, which are 13 and 40 cm from the left edge of the computer display. The plus sign shows the location of the reference line, which is at 122 cm from the left edge of the computer display. The distance of the left eye to the screen is 32 cm. The distance from the left eye to the straight ahead position on the screen is 42 cm.

**Design**

Four main orientations of the reference line were used: 45 degrees, -45 degrees, 0 degrees (horizontal line), and 90 degrees (vertical line) with respect to the horizontal. Here we have used the convention that +45 degrees corresponds to a counter-clockwise rotation over 45 degrees of a horizontal line.

An additional scatter of 2 or 4 degrees was added to these main orientations. So, for example, for the 45 degrees orientation, the reference line could be presented at an orientation of 41, 43, 45, 47, or 49 degrees. The participants were told that some scatter had been added to the orientation of the line, so that it would be important to align the two orientations instead.
of, for example, matching some preconceived orientation relative to external cues, such as gravity or the edges of the screen.

Each combination of the four main orientations and the three matching locations was presented 10 times to each participant. This resulted in a total of 120 trials, which took each of the participants about 30 minutes to complete.

For each trial the orientation of the matching line was selected at random from a uniform distribution in the range from 0 to 180 degrees. The order of the trials was randomized across participants.

Procedure

Participants were seated in a chair at either the left or the right of the computer screen, depending on the viewing position condition. The height of the chair was adjusted such that the participants were viewing it at the same height as they would be viewing the screen when they would be standing. This was done to make the results comparable to those of Experiments 2 and 3, in which participants were standing.

At the beginning of each trial two lines each consisting of seven dots appeared on the screen and the participant was asked to rotate the matching line using the computer keyboard, until they thought the two lines looked parallel.

After the participant had pressed the button to ask for the next trial a 1000 ms intertrial interval was started in which the screen was cleared. After this interval two new lines were plotted on the screen.

Data Analysis

For each trial two error measures were computed: A signed error and an unsigned error. The signed error was computed as the difference between the orientation of the reference line and the matching line. The unsigned error was the absolute value of the signed error. Statistical tests using means per participant were conducted to test for each reference line orientation and matching line location whether the orientations of the matching lines were different from the orientations of the corresponding reference lines. Additional tests were carried out to check whether systematic errors differed for the different positions of the matching line. To test for the oblique effect the unsigned errors of the oblique orientations were compared with those of the orthogonal orientations using participants as a random factor. In a two-way
MANOVA the effects of orientation (oblique/orthogonal) and matching line location were tested. Undirectional tests were used.

3.2.2 Results

In Figures 3.2 and 3.3 the produced orientations are plotted for the left and the right viewing position, respectively, together with the orientations of the reference lines for each of the locations of the matching line. Longer lines represent the orientations of the reference lines, shorter lines the orientations of the matching lines. Results of statistical tests are included in the figure. A tilde sign indicates that the mean of the produced orientations did not significantly differ from the orientations of the reference lines. One asterisk denotes an effect at a significance level of 5%, and a double asterisk represents an effect at a significance level of 1% (all effects were corrected for the number of tests using a Bonferroni correction). The reference lines are plotted at the same location as the matching line for a convenient comparison with the matching lines. In fact the reference stimuli were to the right of the plot. Mean signed errors (an indication of the size of systematic errors) and mean standard deviations (an indication of the size of variable errors) across participants are presented in Table 3.1.

Systematic errors were found for the oblique but not for the horizontal and vertical (‘orthogonal’) orientations, both for the left and the right viewing position. However, for the -45 degrees orientation at the lower right presentation location no differences were found between reference and matching line orientations. For the left viewing position there was a small difference between the orientation of the matching line and reference line for the 45 degrees orientation at the upper right location, but this difference did not reach significance.

Unsigned errors between oblique and orthogonal orientations were compared to see whether an oblique effect was present in our data set. For the left viewing position an oblique effect was found ($F(1, 5) = 18.098$, $p = 0.008$), which did not significantly interact with matching line location ($F(2, 4) = 4.358$, $p = 0.099$). There was an oblique effect for the right viewing position too ($F(1, 6) = 10.746$, $p = 0.017$), which did interact with matching location ($F(2, 5) = 10.022$, $p = 0.018$).

For the left viewing position the produced orientations for the upper left and upper right matching line location were found to be significantly different for the -45 degrees orientation ($t(5) = 5.446$, $p = 0.003$). In addition, for both oblique orientations significant differences were observed for the upper
Table 3.1: Mean signed errors and mean standard deviations across participants observed in Experiment 1. A single asterisk denotes a significant effect at a significance level of 0.05.

<table>
<thead>
<tr>
<th>Location</th>
<th>0 degrees</th>
<th>90 degrees</th>
<th>45 degrees</th>
<th>-45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Viewing Position</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>-2.0417</td>
<td>0.1033</td>
<td>-11.8317*</td>
<td>1.0750</td>
</tr>
<tr>
<td></td>
<td>(2.0716)</td>
<td>(2.2650)</td>
<td>(3.6154)</td>
<td>(2.5409)</td>
</tr>
<tr>
<td>Upper left</td>
<td>1.1083</td>
<td>-0.090</td>
<td>-8.2400*</td>
<td>11.7033*</td>
</tr>
<tr>
<td></td>
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<td>(2.5614)</td>
<td>(3.2109)</td>
<td>(4.0438)</td>
</tr>
<tr>
<td>Upper right</td>
<td>-3.7500</td>
<td>0.1183</td>
<td>-5.2550</td>
<td>6.6783*</td>
</tr>
<tr>
<td></td>
<td>(11.8363)</td>
<td>(3.1027)</td>
<td>(6.8526)</td>
<td>(4.1006)</td>
</tr>
<tr>
<td><strong>Right Viewing Position</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower right</td>
<td>1.4157</td>
<td>-0.1700</td>
<td>7.2271*</td>
<td>-3.3314</td>
</tr>
<tr>
<td></td>
<td>(1.8963)</td>
<td>(2.7154)</td>
<td>(4.0560)</td>
<td>(3.2260)</td>
</tr>
<tr>
<td>Upper left</td>
<td>0.1786</td>
<td>-0.5529</td>
<td>7.8929*</td>
<td>-5.6486*</td>
</tr>
<tr>
<td></td>
<td>(1.4708)</td>
<td>(3.1198)</td>
<td>(6.3491)</td>
<td>(3.8877)</td>
</tr>
<tr>
<td>Upper right</td>
<td>0.4529</td>
<td>-0.0614</td>
<td>6.3957*</td>
<td>-4.8371*</td>
</tr>
<tr>
<td></td>
<td>(1.6580)</td>
<td>(2.9302)</td>
<td>(2.5904)</td>
<td>(3.0944)</td>
</tr>
</tbody>
</table>
Figure 3.2: Orientations of the reference lines (longer lines) together with the matching line orientations (shorter lines). The plot presents results from all trials from all participants. The symbols near the lines show whether the corresponding difference between the orientations of the reference and the matching lines were significantly different. A tilde sign denotes a nonsignificant effect. A single asterisk represents a significant effect at a significance level of 0.05.

right and lower right matching line location (-45 degrees: $t(5) = -5.880, p = 0.002$; 45 degrees: $t(5) = -3.725, p = -0.0014$). For the right viewing position no differences were found between the systematic errors for the upper left and upper right matching line position. Neither were there significant differences between errors for the upper and lower right position.

### 3.2.3 Discussion

The results in Figs. 3.2 and 3.3 can be best summarized by stating that the orientation of an oblique line is perceived to be more oriented towards the vertical at more nearby locations (Fig. 2). This is equivalent to stating that the orientation of an oblique line is perceived to be more oriented towards the horizontal at more distal locations. In Figure 3.2 the matching line was presented nearby while the reference line was farther away. Because lines farther away seem to be perceived more oriented to the vertical, participants rotated the nearby matching line towards the vertical to match the
Figure 3.3: Orientations of the reference lines together with the produced orientations. The plot presents results from all trials from all participants. The data for the right viewing position are shown. As in Figure 3.2 symbols near the lines indicate whether the orientations of the matching and the reference lines were significantly different.

perceived orientation of the reference line. In Figure 3.3 the reference line was presented nearby and the matching line was farther away. In this condition the distant matching line was perceived to be oriented more to the vertical such that participants rotated its orientation towards the horizontal to match the perceived orientation of the nearby reference line.

In a previous study on haptic perception, Kappers and Koenderink (1999) reported that differences between the orientation of a reference bar and a matching bar increased for larger angles between the reference bar and matching bar relative to the subject. The radial distance relative to the subject did not appear to have any effect. That study dealt with bars in a horizontal plane, whereas our study dealt with the orientation of lines in a vertical plane. Therefore, it is appropriate to address the question to what extent any differences in orientation of the matching line and reference line in our study have to be attributed to the different viewing angle or to the different distances of the lines relative to the observer. The results of viewing from the left and right side are compatible with both hypotheses. Therefore, we did a pilot experiment, in which we asked two subjects, who also participated in
the first experiment, to visually match the same stimuli of experiment one, while sitting right in front of the screen at a distance of about 32 cm. In this condition the distances of the participant relative to the reference line and the upper left matching line are the same and the viewing angle in this condition is much larger than for the same stimuli in Experiment 1. The results revealed much smaller consistent (signed) errors for the oblique stimuli, suggesting that the errors have to be attributed mainly to distance, rather than to the viewing angle.

Only few studies on visual perception have tested subjects in viewing conditions other than straight ahead. Some experiments have been carried out in which a drawing or a picture was looked at from different angles (Cutting, 1988; Deregowksi & Parker, 1995; Goldstein, 1987; Halloran, 1993). In these experiments drawings were shown in which perspective was used to suggest a 3D scene. For example, Goldstein (1987) presented a picture of three columns in a 3D scene to participants, and asked them to estimate the distance in depth from one column to the other. Estimated depth and perceived orientations of painted objects were found to be quite independent of viewing angle, an effect known as the ‘differential rotation effect’. In our experiments we did not try to induce depth in our stimuli. The stimuli were 2D lines with no intention to make them look as if they would point outside the plane of the screen. In fact, none of our participants reported that they perceived the lines coming outside the plane of the screen. In addition, we found a strong effect of viewing position, and therefore, the ‘differential rotation effect’ does not apply to our data.

3.3 Experiment 2

In the second experiment we tested whether the systematic effects found in Experiment 1 for visual matching in the vertical plane are also found when participants have to match the orientation of the perceived line using a handheld bar.

3.3.1 Method

Participants

Seven participants took part in the experiment. Two of them were the authors. Five of the participants had also participated in Experiment 1.
Two participants were paid for taking part. All participants had normal or corrected-to-normal vision.

**Apparatus**

For stimulus presentation the same PC and LCD projector were used as in Experiment 1. In Experiment 2 participants were asked to match the orientation of the reference bar by adjusting the orientation of a hand-held bar. The bar used was 29 cm long and weighted 0.32 kg. The orientation of the bar was measured using the Optotrak 3020 system (Northern Digital Inc.), which determined the position of two infra-red light-emitting diodes (IREDs), attached to the bar at a distance of 20 cm. The accuracy of the orientation of the bar could be measured with an accuracy better than 0.5 degrees.

**Stimuli and Design**

The stimuli and the design of the experiment were almost the same as in Experiment 1. Instead of the matching line a small circle was presented at the location of the matching line in the first experiment. This circle indicated to the participant where to match the orientation of the reference line by the orientation of the hand-held bar.

**Procedure**

Participants were standing at the left position illustrated in Figure 3.1. All participants were asked to hold the bar in their right hand, although two participants were left-handed. No differences were found in the pattern of results for the left-handed and right-handed participants. Participants were instructed to use a power grip to hold the bar. At the beginning of each trial the reference line appeared at the upper right of the screen (same as in Experiment 1), and a circle appeared at one of the three matching locations (upper left, upper right, or lower right). Participants would then move the hand-held bar towards the location of the circle while orienting the bar such that they thought its orientation matched that of the reference bar. Two seconds after the presentation of the line an auditory signal told the participant to hold the orientation of the bar as fixed as possible. A second tone, presented 1500 after the first tone, indicated that the arm could be moved back to the starting position near the waist. During the interval between the
Table 3.2: Mean signed errors and mean standard deviations across participants observed in Experiment 2. A single asterisk denotes a significant effect at a significance level of 0.05. Double asterisks represent significant effects at a significance level of 0.01.

<table>
<thead>
<tr>
<th>Location</th>
<th>0 degrees</th>
<th>90 degrees</th>
<th>45 degrees</th>
<th>-45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower right</td>
<td>-0.4978</td>
<td>0.3771</td>
<td>-10.1933**</td>
<td>4.1686</td>
</tr>
<tr>
<td></td>
<td>(2.3613)</td>
<td>(3.8801)</td>
<td>(5.1686)</td>
<td>(3.3705)</td>
</tr>
<tr>
<td>Upper left</td>
<td>-1.5171</td>
<td>1.4234</td>
<td>-5.9513*</td>
<td>12.1187**</td>
</tr>
<tr>
<td></td>
<td>(2.2855)</td>
<td>(3.0848)</td>
<td>(4.2122)</td>
<td>(4.0941)</td>
</tr>
<tr>
<td>Upper right</td>
<td>0.1427</td>
<td>0.1154</td>
<td>-7.5173**</td>
<td>8.8953**</td>
</tr>
<tr>
<td></td>
<td>(2.5358)</td>
<td>(3.1121)</td>
<td>(4.8091)</td>
<td>(2.9565)</td>
</tr>
</tbody>
</table>

For the reference line, the orientation of the bar was measured by the Optotrak system. After each 30 trials there was a break of about a minute.

**Data analysis**

The mean location (averaged over 90 samples) of each IRED during the measurement period was calculated. Trials in which one of the IREDS was not visible for the Optotrak system (about 5 trials per participant) or in which participants moved the bar during the period in which the Optotrak system measured the orientation of the bar (about two trials per participant), were removed from the data analysis. For the remaining trials the orientation of the bar was calculated by fitting a line through the two mean IRED locations.

The calculated orientations were analyzed in the same way as those observed in Experiment 1.

**3.3.2 Results**

In Figure 3.4 the orientations of the hand-held bar are shown together with the orientations of the reference line. Data of all participants are plotted in one figure. The symbols near the lines present the significance level of the differences between matching and reference line orientations across participants. The mean errors and mean standard deviations across participants are shown in Table 3.2.

The orientations of the matching lines for the upper right and lower right stimulus location differed for the -45 degrees orientation ($t(6) = -3.917$, $p = 0.008$), but not for the 45 degrees orientation ($t(6) = -2.380$, $p = 0.055$).
Figure 3.4: Orientations of the reference lines together with the orientations of the matching lines for all participants for the three matching locations. The symbols near the lines indicate whether the orientations of the reference lines were significantly different from those of the matching lines (̃ no significant difference; * and ** significantly different with respect to 5% and 1% significance level, respectively).

Differences were found between orientations produced at the upper left and upper right stimulus location both for the 45 degrees orientation ($t(6) = 3.971$, $p = 0.007$) and the -45 degrees orientation ($t(6) = 4.933$, $p = 0.003$). A clear oblique effect was found ($F(1, 6) = 312.479$, $p < 0.01$), which did not interact with stimulus location ($F(2, 4) = 2.861$, $p = 0.148$).

Since five of the participants of Experiment 2 also took part in Experiment 1, it was possible to compare the size of the effects in both experiments directly. For this comparison data from the left viewing position of Experiment 1 were used. Figure 3.5 shows the produced orientations of Experiment 1 in the outer circle, together with the orientations of Experiment 2 in the inner circle. The symbols near the lines indicate the significance level of the differences in signed errors. No significant differences were found for signed and unsigned errors in experiments 1 and 2.
3.3.3 Discussion

Both for haptic and visual matching systematic errors were found for the oblique orientations but not for the horizontal and vertical orientations. The direction and size of the effects were the same for both matching tasks.

One could argue that vision of the edges of the screen near the matching stimulus might have resulted in the lack of systematic effects for the orthogonal orientations in Experiment 1 and 2. Participants might have compared the matching line orientation to the edges of the screen. To see whether participants actually used this information, scatter was added to the reference orientations. If participants used the edges of the screen to orient the matching line orientations, smaller correlations between orientations of matching and reference lines are expected for orthogonal than for oblique orientations, since the edges were a better reference for vertical and horizontal orientations.

Table 3.3 shows the values of these correlations. The correlations shown were computed within each main orientation. Therefore, they summarize how accurate participants were at matching the small variations of a few degrees around each main orientation. For all three matching conditions correlations

Figure 3.5: Orientations of matching lines of Experiments 1 and 2. The lines at the outer circle show the orientations of Experiment 1, those in the inner circle of Experiment 2. The symbols near the lines show whether the orientations in the two experiments differed significantly. Tilde signs denote nonsignificant effects.
Table 3.3: Mean correlations (Pearson product-moment correlation coefficient) across participants between presented and produced orientations for Experiments 1 and 2.

<table>
<thead>
<tr>
<th>Main orientation</th>
<th>Experiment 1, left</th>
<th>Experiment 1, right</th>
<th>Experiment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 degrees</td>
<td>0.55</td>
<td>0.81</td>
<td>0.60</td>
</tr>
<tr>
<td>90 degrees</td>
<td>0.52</td>
<td>0.80</td>
<td>0.38</td>
</tr>
<tr>
<td>45 degrees</td>
<td>0.35</td>
<td>0.61</td>
<td>0.20</td>
</tr>
<tr>
<td>-45 degrees</td>
<td>0.36</td>
<td>0.53</td>
<td>0.21</td>
</tr>
</tbody>
</table>

were higher for the orthogonal than for the oblique directions with mean values near 0.60 and 0.37, respectively. This implies that participants better matched the small variations in orientation for the orthogonal directions than for the oblique directions, which obviously argues against the use of the edges of the screen to match lines at orthogonal directions.

Additionally, if participants used the edges of the screen, larger matching errors for orthogonal orientations were expected for matching locations farther away from the edges of the screen. This was not found. Participants matched the orthogonal orientations equally correct for all three matching locations.

Participants might have carried out the haptic matching of Experiment 2 as if it were a visual matching task, since they had sufficient time to reorient the bar before its orientation was measured. If participants strongly relied on the visually perceived orientation of the bar similar results should be expected in Experiments 1 and 2.

In Experiment 3 a mask made the bar and the hand invisible to the participant while matching the visually presented orientation. If participants of Experiment 2 relied primarily on visual information of the orientation of the bar and if haptic and visual matching actually result in different matched orientations, different results have to be expected for experiments 2 and 3.

### 3.4 Experiment 3

In Experiment 3 participants were asked to match the orientation of a reference line by orienting a hand-held bar. The field of view was restricted to the reference line by a piece of cardboard which occluded the remainder of the visual field. Although hand and bar could not be seen, participants
could see the reference line while matching its orientation.

3.4.1 Method

Participants

Seven participants took part in the experiment. Two of them were the authors. Two participants were paid for their participation. All participants had normal or corrected-to-normal vision. Two participants were left-handed.

Apparatus and stimuli

Apparatus and stimuli were the same as in Experiment 2. A piece of cardboard prevented the participants from seeing their hand and the bar while matching the reference orientation.

Design

Each participant took part in two sessions of 120 trials each. The number of trials was doubled with respect to the first two experiments because the variance in the produced orientations was found to be much larger without than with visual feedback. In all other aspects the design of the experiment was the same as in Experiment 2.

Procedure

There was one difference with respect to the procedure of Experiment 2: A piece of cardboard prevented participants to see their hand and the bar while matching the orientation of the reference line. Participants were asked to keep fixating the reference stimulus while matching its orientation. Below the reference line the Dutch words for ‘upper left’, ‘lower right’, and ‘upper right’ were printed to indicate the location at which the orientation had to be matched (the same locations as in Experiments 1 and 2). At the beginning of the experiment participants held their hands at the locations where they thought they would have to match the orientation, in order to agree on the locations to be used. During the experiment the experimenter watched where participants matched the reference location. If the bar was held at a location closer to one of the other matching locations than to the instructed matching location the experimenter would tell the participant in which direction to change the location of the bar.
Participants did not always hold the bar at exactly the matching location, since they could not see where they were holding their hand while matching. The mean coordinates of the locations, where the bar was held, were 33 cm from the left and 27 cm from the top (33 cm, 27 cm) of the computer display for the upper left condition, (99 cm, 35 cm) for the upper right location, and (113 cm, 133 cm) for the lower right location.

Data analysis

For each trial the location of the center of the two IREDs at each side of the bar was computed. This center location was entered in a three-means clustering algorithm where the instructed locations were used as starting values. This way the produced locations were grouped into three clusters together with the corresponding produced orientations. The orientations of each cluster were analyzed with the same data analysis procedures as used in Experiments 1 and 2.

3.4.2 Results

Orientations of reference and matching lines are plotted in Figure 3.6. The orientations are presented at the location at which participants had to match the reference orientation. Data of all participants are plotted in one figure, as was done for Experiments 1 and 2. Near the lines the results of t-tests testing the difference between reference and matching line orientations are shown. As in Experiments 1 and 2 significant differences were found for the oblique orientations, except for the -45 degrees orientation at the lower right location. Mean errors and mean standard deviations across participants are presented in Table 3.4.

No significant difference was found between signed errors for the upper left and the upper right position (for the -45 degrees orientation: $t(6) = 1.385$, $p = 0.215$, for the 45 degrees orientation: $t(6) = 1.760$, $p = 0.129$). The signed errors for the oblique orientations at the upper right and lower right position were significantly different (for the -45 degrees orientation: $t(6) = 2.507$, $p = 0.046$, for the 45 degrees orientation: $t(5) = 6.746$, $p = 0.001$).

Unsigned errors for oblique and orthogonal directions were significantly different ($F(1, 6) = 28.377$, $p = 0.002$). The oblique effect did not interact with stimulus position ($F(2, 5) = 0.144$, $p = 0.870$).
Figure 3.6: The orientations of the reference lines (long lines) together with the matched orientations (short lines) for all participants. The symbols near the lines show whether the orientations of the matching and reference lines were significantly different. A tilde sign denotes a non-significant effect, a single asterisk a significant difference at a significance level of 0.05, and a double asterisk at a significance level of 0.01.

Because five of the participants of Experiment 3 also participated in Experiment 2, the results of both experiments could be compared using within subjects tests. In Figure 3.7 the produced orientations in both experiments are shown. The lines at the outer circle present data from Experiment 3, and lines at the inner circle data from Experiment 2. The symbols near the lines show the outcomes of t-tests comparing the signed errors of both experiments. As the symbols show, no significant differences were found in the signed errors of the two experiments.

In a three-way MANOVA the effects on unsigned errors of matching condition (with or without visual feedback), matching line location, and reference line orientation were tested. Significant effects of matching condition ($p = 0.030$) and reference line orientation ($p = 0.002$) were found. No interaction effects were found.
Table 3.4: Mean signed errors and mean standard deviations across participants observed in Experiment 3. A single (double) asterisk denotes a significant effect at a significance level of 0.05 (0.01).

<table>
<thead>
<tr>
<th>Location</th>
<th>0 degrees</th>
<th>90 degrees</th>
<th>45 degrees</th>
<th>-45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower right</td>
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<td>0.2877 (4.8218)</td>
<td>-12.1142** (6.6763)</td>
<td>-2.1080 (6.4514)</td>
</tr>
<tr>
<td>Upper left</td>
<td>-5.8967 (5.7180)</td>
<td>-2.1210 (6.1586)</td>
<td>-6.7651* (7.9533)</td>
<td>9.2611* (5.1658)</td>
</tr>
<tr>
<td>Upper right</td>
<td>-4.0328 (4.4919)</td>
<td>-1.0419 (6.0510)</td>
<td>-8.3715* (6.4237)</td>
<td>7.0739* (3.2532)</td>
</tr>
</tbody>
</table>

Figure 3.7: Produced orientations for Experiments 2 and 3. Lines at the outer circle show data of Experiment 3, those at the inner circle of Experiment 2. The symbols near the lines show whether orientations significantly differed for the two experiments. Tilde signs denote nonsignificant effects.

3.4.3 Discussion

The design of Experiment 3 was somewhat similar to that used by Soechting and Flanders (1993), who asked participants to match the orientation of a visually presented bar with a bar at waist level. In their study participants always fixated the reference bar during the matching task so that they had no visual information about the orientation of the matching bar near their
waist. Systematic errors were reported for slanted orientations but not for horizontal and vertical orientations of the reference bar. In this respect their data are similar to ours. Unfortunately, subjects in their study and in our study viewed the stimuli from very different viewing angles. In our experiment participants looked at the reference lines from aside (either from the left or from the right), while in the experiment by Soechting and Flanders the stimuli were presented in front of the participants. Since Experiment 1 showed that viewing position has an effect on matching errors, the different viewing positions of the participants make it difficult to compare the results of the two studies quantitatively.

An oblique effect was found by comparing unsigned errors. Based on the variability of matching in Figure 3.6 this may be somewhat surprising. Figure 3.6 does not seem to show a large oblique effect, since oblique orientations seem to be produced with almost the same accuracy as orthogonal directions. A reason for the unexpected oblique effect might be the use of unsigned errors to test for the oblique effect (see for example, Luyat, Gentaz, Corte, & Guerraz, 2001). In the presence of systematic errors it might be better to test for differences in variance. We have used the variance to test for an oblique effect in our data and found no significant oblique effect ($p = 0.168$) with this measure.

### 3.5 General discussion

We have found clear systematic effects when visually presented oblique orientations had to be matched in three different tasks: (1) visual matching, (2) haptic matching with visual feedback, and (3) haptic matching without visual feedback. The systematic errors were identical for the three matching situations, not only qualitatively but also quantitatively.

Part of the explanation of the matching errors might be that participants could not fully correct for geometric distortion of the two lines on the retina. In general, when two parallel lines are projected on the plane of the retina their projection will not be parallel. Only parallel horizontal and vertical lines will have parallel retinal projections. This might explain why the orientations of horizontal and vertical lines were matched correctly and why systematic errors were found for oblique lines. However, the errors made by the participants were smaller than those expected on the basis of the geometric distortion. Therefore the distortion of orientations by projection on the retina can be only a part of the explanation.
Our study suggests that systematic errors in matching are primarily due to errors in visual perception of the lines, while the variable errors in matching are primarily due to errors in haptics. As explained in the Introduction, errors in visual perception have been reported frequently in the literature. Some studies have reported that motor responses to visual stimuli reflect errors in visual perception, while other studies have suggested that motor responses may be insensitive to errors in visual perception. Obviously, our results are in agreement with the former.
Chapter 4

The structure of fronto-parallel haptic space is task dependent.\(^3\)

\(^3\)Adapted from: Hermens, F., Kappers, A.M.L., & Gielen, S. (submitted)
4.1 Introduction

Several studies have aimed at determining the relationship between the structure of perceived visual space and Euclidean physical space (for an overview, see Wagner, 1985). The structure of visual space has been investigated using several experimental methods, including distance matching (Meng & Sedgwick, 2001), orientation matching (Cuijpers, Kappers, & Koenderink, 2002), triangulation (Fukusima, Loomis, & Da Silva, 1997), pointing (Koenderink, Van Doorn, Kappers, & Lappin, 2003), and direct testing of axioms (Koenderink, Van Doorn, Kappers, & Todd, 2002; Todd, Oomes, Koenderink, & Kappers, 2001). One of the aims of these experiments was to test to which extent the assumption of Luneburg (1947) holds, that perceived space has a Riemannian structure with a negative curvature. For visual and haptic orientation matching tasks Cuijpers (2003) showed that a zero curvature yields the best fit of the data. In addition, they showed that for other tasks, such as the pointing task, a Riemannian space did not yield an appropriate fit.

These investigations of visual space have been extended to the haptic modality. Blumenfeld (1937) asked participants to match the orientation of two strings, which were at one side attached to a table. In this matching task participants made systematic errors. Successive experiments investigated the so-called oblique effect (Appelle & Countryman, 1986; Appelle & Gravetter, 1985; Gentaz & Hatwell, 1995, 1999; Lechelt, Eliuk, & Tanne, 1976; Lechelt & Verenka, 1980). The focus of these studies was the oblique effect on variable errors: Horizontal and vertical orientations can be estimated with smaller variability than oblique orientations. Later studies also investigated the oblique effect on systematic errors (e.g., Kappers, 2003).

These studies of the haptic oblique effect showed that several factors affect the size of the oblique effect. The effect was larger when participants performed the matching task using both hands (bimanual matching) than when they used the same hand for inspection and matching (unimanual matching, see Appelle & Countryman, 1986; Gentaz & Hatwell, 1995). The variability in the settings typically decreased when participants performed the matching after a delay between inspection and matching (Lechelt & Verenka, 1980). Certain tasks during the delay, such as the recall of the letters of the alphabet in reversed order, also affected the variability of the settings (Gentaz & Hatwell, 1999). In addition, the matching variability depended on the orientation of the plane (horizontal, frontal, or sagittal) in which the matching is performed (Gentaz & Hatwell, 1995, 1996). The effect of the matching plane is thought to be due to gravitational cues (see also Luyat et al., 2001), but
might also be related to forearm orientation (Soechting & Flanders, 1993; Kappers, 2003). Gentaz and Hatwell (1996, 1999) showed that errors were different in conditions where participants could rest their arms on the table and in conditions where they were asked to hold their arms just above the table surface.

The oblique effect experiments were followed by a series of haptic space studies (Kappers, 1999, 2002, 2003; Kappers & Koenderink, 1999; Newport, Rabb, & Jackson, 2002; Zuidhoek, Kappers, Lubbe, & Postma, 2003). In these experiments the focus was on determining the structure of the internal representation of space on the basis of haptic perception of object orientations. Because of the different research question with respect to the studies of the oblique effect, there were differences in the data collection and the data analysis. One difference involves the number of locations at which the stimuli were presented. Most of the haptic space studies presented stimuli at several positions within a large part of the workspace, while the oblique effect studies often presented stimuli at a few (in general one or two) positions only. Another difference between the oblique effect studies and the haptic space studies relates to the type of errors that are studied. While the oblique effect studies focused on the variability in the settings, the haptic space studies investigated systematic errors.

In their haptic space study, Kappers and Koenderink (1999) investigated the structure of horizontal haptic space by presenting the reference bar at one of nine positions located on a three by three grid. Orientation matching performance was measured for each of the remaining eight positions on the grid. These extensive measurements resulted in vector plots showing the structure of the horizontal haptic space. The vector plots showed that the size of the matching errors increased with the horizontal distance between the two bars. In their study Kappers and Koenderink (1999) presented all stimuli to the right of the participant and asked the participants to use their right hand only to match the orientations of the bars. Kappers (1999) extended their study by looking at bimanual matching across a larger portion of the horizontal space. Large systematic deviations from physical parallelity were found which increased with the horizontal distance between the bars. The errors were larger for bimanual than for unimanual matching. Kappers (2003) performed a further analysis to investigate the factors that might contribute to the large systematic haptic matching errors. When she ordered the participants with respect to their mean error, she found that for participants with a relatively large mean error, the oblique effect on systematic errors reversed: Participants with large mean errors had larger matching errors for
horizontal and vertical orientations than for oblique orientations. Also, she observed that her female participants made larger systematic errors than the male participants. Kappers (2002) investigated the sagittal plane. Also for this plane systematic errors were found, which were larger for bimanual matching. The findings by Kappers (2002) extend earlier measurements of the oblique effect in the sagittal plane, in which stimuli at just two locations were presented (Gentaz & Hatwell, 1995).

In the present study we investigated the structure of haptic space in the fronto-parallel plane using three haptic orientation tasks. In previous studies (Kappers, 1999; Kappers & Koenderink, 1999; Kappers, 2002) the structure of horizontal and sagittal haptic space has been studied. When the structure of the three orthogonal haptic spaces (horizontal, fronto-parallel, and sagittal) is known, the structure of 3-D haptic space might be inferred. It is also interesting to see whether the same properties hold for fronto-parallel haptic space as those found for horizontal haptic space (see, Kappers, 2003).

To investigate fronto-parallel space three tasks were used. In Experiment 1 we asked participants to match the orientation of two bars presented in the fronto-parallel plane. Eight combinations of the two bar locations were used, such that an impression of the structure of haptic space in the frontal plane could be obtained. All the bars were matched bimanually. In this haptic matching experiment, we found that participants made large systematic errors. We hypothesized that these errors could originate from one of the three stages involved in the matching process: (1) The perception of the bars’ orientations, (2) the transfer of the perceived orientation to the matching bar location, (3) and the production of the matching bar orientation. To investigate the errors involved in the perception and the production stages we performed two additional experiments. To investigate the haptic perception of orientation we asked participants to report the orientation of a bar by naming the corresponding clock time, by having them assume the bar was representing the large hand of the clock. The haptic production task involved setting the bars in an instructed orientation. Participants were instructed to rotate each bar such that they thought that it was in the instructed orientation.

4.2 Experiment 1

In Experiment 1 we investigated the structure of fronto-parallel space by asking participants to match the orientation of a reference bar to that of a
matching bar. This matching task has been used before to investigate the structure of horizontal haptic (Kappers, 1999; Kappers & Koenderink, 1999) and visual space, and to investigate the sagittal haptic space (Kappers, 2002). We restricted the number of bar positions to four. By comparing the errors for these four positions within three different tasks (Experiments 1 through 3) a good first impression of fronto-parallel space could be obtained.

4.2.1 Method

Participants

Fifteen participants (seven male) took part in the experiment. We tested the participants on handedness using Corens test (1993). All participants except for one (participant GA) were right-handed. The left-handed participant received the same instruction as the right-handed participants. Seven of the participants were naive with respect to the experimental setup and the haptic matching task. These participants were paid for their participation. The remaining participants had taken part in one or more haptic matching experiments for the horizontal plane. No participant had been involved in a haptic matching experiment for the fronto-parallel plane before.

Six right-handed participants took part in an additional session in which we video recorded their movements and arm postures during matching. Four of these participants also took part in the matching task without video recording.

Apparatus

For the haptic matching task two metal bars were used. These bars were attached to a vertically positioned white-board in the fronto-parallel plane. Each bar had a length of 20 cm a diameter of 1 cm. Each bar could be rotated around its center by the pin attached to its center, which fitted into holes in the white-board. The bars were held in place by two magnets. They could be placed on each of the four corners of a four by four grid measuring 90 by 90 cm. The bar positions were each at a distance of 45 cm of the body mid-line. The top two bar positions were at a distance of 30 cm from the shoulders, the bottom two bar positions were at a distance of 60 cm from the shoulders. On the white-board a sheet was attached showing protractors around each possible bar position. These protractors were used to measure the orientation of the bars, which could be done with an accuracy of one degree. Figures 4.1a and 4.1b show the setup. In Figure 4.1a drawing of a
subject performing the matching task is shown. This drawing shows the four possible bar positions. Figure 1b shows one of the bars with the protractor used to measure its orientation.

![Figure 1a](image1.png) ![Figure 1b](image2.png)

Figure 4.1: Figure 1a shows a schematic of the setup in which a participant performing the matching task. Bars could be presented on each of the four corners of a four by four grid. The letters in the plot indicate the four positions: Upper Left, Upper Right, Bottom Left, and Bottom Right. Figure 1b shows a picture of one of the bars. The bar was attached to the white-board by means of magnets and could rotate around its center. After each trial the experimenter measured the orientation of the bar by looking at the scale printed on a piece of paper that was attached to the white-board.

On each trial one bar was placed on the left side of the body mid-line and the other on the right side. Participants were standing in front of the white-board, at a distance of about 30 cm. The height of the white-board was adjusted for each participant such that the vertical distance between the upper bar positions and the participant’s shoulder was 30 cm. With the white-board in this position all stimuli could be reached easily.

For the video recording of the participants’ movements a mini digital video camera (type Aiptek DV3100+) was used. This camera produced avi video files with a resolution of 320 by 240 pixels.
Design

Eight combinations of the locations of the two bars were used. One bar was presented on the right of the participant and one on the left. The following combinations (reference position - matching position) were used (where UL denotes upper left, UR upper right, BL bottom left, and BR bottom right): UL-UR, UR-UL, UL-BR, BR-UL, BL-UR, UR-BL, BL-BR, and BR-BL. Each of these eight combinations was presented three times for each of the main orientations (horizontal (0 degrees), vertical (90 degrees), and the two oblique orientations: 45, and 135 degrees counterclockwise with respect to the horizontal). The combination of all locations and orientations resulted in 96 trials per participant. The order of the trials was randomized across participants. In order to prevent that participants would match an imaginary orientation of 0, 90, 45, 135 degrees orientation, the main orientation, the main orientation minus 10 degrees, and the main orientation plus 10 degrees were each presented once. For example, for the 45 degrees orientation, the orientations 35, 45, and 55 degrees were used.

The six additional participants, whose movements were video recorded, received only one set of 32 trials, which included 4 main orientations and 8 combinations of reference bar and matching bar locations.

Procedure

Before the start of the experiment, the experimental task was explained to the participant. The experimenter showed two pens on the table and rotated one pen such that its orientation matched the orientation of the other pen. The participant was explained that in the experiment bars would be used instead of pens, and that the task should be performed by touch instead of by vision. Following the instruction the participant was blindfolded and guided to the white-board. Participants did not see the setup until after the experiment.

At the beginning of each trial the reference and the matching bar were positioned at the pre-selected locations, which were printed on a list. The experimenter then rotated the reference bar to the pre-selected orientation. The orientation of the matching bar was set in a random orientation which was at least 10 degrees off the orientation of the reference bar. Before each trial the experimenter told the participant which bar was the reference bar and which bar had to be rotated. If the participant rotated the incorrect bar, the reference bar was set to its original orientation and the trial was rerun. Participants were allowed as much time as they wanted for inspection of the
reference bar and for setting the orientation of the matching bar. Typically participants took about 10 seconds per trial. They were asked to touch the bars with the inside of their hands and to stand upright without bending their knees. Bars on the left had to be touched with the left hand and bars on the right with the right hand. When the participant indicated to be satisfied with the setting, the experimenter determined the orientation of the matching bar by looking at the protractor on the white-board.

The experiment was divided into two blocks with a short break in between, in which participants were guided to the other side of the room. This allowed them to take off their blindfold during the breaks without seeing the setup.

The participants of the video recorded version of the experiment performed all their trials in one block, which took them about 15 minutes. The participants who were familiar with haptic matching experiments were told that any orientation could be presented and that it would be important to match the perceived orientation. The remaining two participants did not receive any information about the orientations used in the matching task.

The video recordings were analyzed after the experiment. From the video files the frames were extracted in which participants almost finished their trial, just before they released the bars. In these frames the location of the shoulder, the elbow, the hand, and the tip of the middle finger were determined visually by mouse clicks on the image of the frame. The locations were used to determine the orientation of the upper arm, the forearm, and the hand in space. For two participants the hand and forearm orientations at the begin of the haptic inspection movements were measured. This was done to investigate whether the initial hand and forearm or the final hand and forearm orientations affected the matching errors.

4.2.2 Results

Participants made large errors in matching the orientation of the matching bar with that of the reference bar. Figure 4.2 shows the errors made by participant MA. The other participants made errors in the same direction as participant MA. Only the size of the errors differed across participants. Participant MA made relatively large errors. The errors shown in Figure 2 are shown with respect to their corresponding main orientation (either 0, 90, 45, or -45 degrees). For example, if a participant matched a reference orientation of 55 degrees with a matching orientation of 70 degrees a line with an orientation of 70 (matching bar)-55 (reference bar)+45 (main orientation)=60
degrees is shown.

Figure 4.2: Signed errors of participant MA. The thick lines show the presented main orientations. The thin lines show the mean orientations produced by the participant with respect to the main orientations. The numbers in the plot show the size of the mean signed error.

Figure 4.2 shows that if the orientation of a bar on the right is matched with that of a bar on the left, its orientation is rotated clockwise (a positive deviation). If the orientation of a bar on the left is matched with that of a bar on the right, its orientation is rotated counter-clockwise (a negative deviation). We used this fact when computing the mean signed errors. The mean signed errors were defined as the orientation of the left bar minus the orientation of the right bar, which resulted in mainly positive deviations.

The mean signed errors are shown in Figure 4.3. In this plot means across participants and matching direction (from left to right and from right to left) are shown. The first two sets of bars of the plot show the horizontal and vertical orientations, and the last two sets of bars show the oblique orientations. In an analysis of variance we tested the effects of stimulus position (8 levels) and orientation (4 levels). A significant interaction effect
was found \((F(7.3, 98; 	ext{Greenhouse-Geisser}) = 5.078, \ p < 0.001)\). The main
effect of location \((F(7, 8) = 12.201, \ p < 0.01)\) was significant. No main
effect of orientation was found \((p > 0.2)\). The analysis showed that overall the
signed errors were significantly different from zero \((F(1, 13) = 57.388, \ p <
0.001)\). Only one simple effect was consistent across conditions: For each
presented orientation, the errors were larger when the reference bar and the
matching bar were presented at the bottom of the white-board (all p-values
for each orientation < 0.05).

![Figure 4.3: Mean signed errors per reference bar orientation and matching
and reference bar location. Means across participants are shown. The lines
on top of the bars shown the 95% confidence intervals.](image)

Kappers (2003) showed that systematic matching errors for the horizon-
tal plane were subject dependent. At large stimulus distances, participants
with relatively small errors showed a standard oblique effect on systematic er-
rors: The mean signed errors were smaller for the horizontal and the vertical
orientation than for oblique orientations. Participants with relatively large
errors showed a reversed oblique effect: They made smaller errors for oblique
orientations. We obtained the same result for our data in the fronto-parallel
plane. Figure 4.4 shows the size of the errors for oblique and orthogonal orientations as a function of the mean error across all conditions. Each pair of data points (connected by a dashed line) represents data from one participant. Two regression lines (one to the data for 0 and 90 degrees (solid line) and one to the data for the 45 and 135 degrees orientations (dotted line)) with different slopes and intercepts yield a significantly better fit of the data than a single regression line ($F(2, 10) = 4.8231, p = 0.05$).

![Figure 4.4: Mean signed error per orientation (0/90 versus 45/135 degrees) plotted against the mean overall error. Each pair of data points (connected by dashed lines) shows the data of one participant. Also included in the plot are the regression lines (a solid line for the 0/90 orientations and a dotted line for the 45/135 orientations).](image)

Kappers (2003) showed that the size of the matching errors for the horizontal plane is gender dependent. Female participants made larger errors than male participants. Figure 4.5 shows that a strong tendency towards this effect is also present in our data for the fronto-parallel plane, which is confirmed by a one-sided t-test ($t(12) = 1.749, p = 0.053$).

Since six participants in our experiments were PhD students of the de-
partment who had heard about the systematic errors in haptic matching experiments before, we could test whether this knowledge did have an effect on the size of the errors. This did not appear to be the case: The systematic errors of the PhD students did not differ in size from those of the naive participants ($t(14) = 0.367$, $p = 0.72$).

Six other participants were video recorded while they performed 32 matching trials. We correlated the difference in hand orientation (left hand orientation minus right hand orientation) at the end of the matching movements with the signed error in the settings. No significant correlation was found across participants (mean= $-0.1457$, $p > 0.1$). We also computed the correlation between the difference in forearm orientation and the size of the signed errors. Also for the forearm orientations no substantial correlations were found (mean= $-0.1701$, $p > 0.1$). An analysis of the forearm and hand orientation data of two participants at the beginning of the movements did not show higher correlations with the errors. In addition, visual inspection of the hand and forearm orientations and the bar orientations did not reveal
any other obvious relationship.

4.2.3 Discussion

Participants made large errors when haptically matching the orientation of a bar with that of a reference bar. The errors showed a specific pattern: The orientation of a reference bar on the left was matched with an clockwise rotated orientation on the right. For the reference bars on the right the opposite matching pattern was observed: They were matched with an orientation which was rotated counter-clockwise with respect to the reference orientation. This pattern of results indicated that the haptic space used by the participants to perform the matching task is systematically deformed with respect to veridical.

We were able to replicate the reversed oblique effect found by Kappers (2003) for the horizontal plane. She found that for large distances between the matching bar and the reference bar participants with relatively large matching errors tend to have larger errors for the horizontal and vertical orientations than for the oblique orientations. The fact that we could replicate this finding for the fronto-parallel plane suggests that similar mechanisms underlie the matching errors. Kappers (2003) showed that for stimuli at larger distances the hands were placed on the bar such that for oblique orientations the stimuli were aligned or perpendicular to the hand. Horizontal and vertical bar orientations had an oblique orientation with respect to the hand. Participants with large deviations are biased by an egocentric frame. An oblique effect in this egocentric reference frame would result in a reversed oblique effect in a physical reference frame.

For the mid-sagittal plane Kappers (2002) showed that the vertical distance between the reference bar and the matching bar determined to a large extent the size of the matching errors. Our experimental design did not allow for the same comparison for the frontal plane. However, we found that the vertical positions of the two bars relative to the participant affected the size of the errors: Errors were larger when the reference stimulus and the matching stimulus were presented at the bottom of the white-board. This finding might be related to the fact that many participants reported that they found the hand orientation for the bottom positions unnatural.

Kappers (2003) showed that female participants make larger matching errors than male participants. Our findings for the fronto-parallel plane agree with her finding. The origin of the difference in female and male participants performance is not known. A study by Van Mier et al. (2003) has shown
that the difference in matching performance is already present at an age of 6.

We were not able to quantitatively replicate Soechting and Flanders’ (1993) and Kappers’ (2003) interpretation that the matching errors are related to egocentric (forearm or hand related) coordinates. Our failure to find a relationship between forearm or hand orientation and matching errors might have been due to the limited number of positions of the reference and matching bar used in our study. Across trials with the same bar positions hand and forearm orientations did not vary much. The main part of the variation in the hand and forearm orientations was due to the bar position. Only eight combinations of reference bar orientation and matching bar orientation were used which were symmetrical in pairs. This small number of bar positions might have resulted in the small correlation between hand orientation and the size of the errors that we observed. Another possibility is that the failure to replicate the correlation between hand orientation and the size of the error was due to the method for measuring the hand orientations. In our experiment we measure hand orientations while participants were performing the matching task. Kappers (2003) determined the participants’ hand orientation by asking them to put their hand at the bar position, without performing the matching task. Soechting and Flanders (1993) varied the arm posture by asking participants to match the reference bar at different positions in space. Although we could not quantitatively replicate the relationship between hand or forearm orientation and the size of the matching errors, the direction of the matching errors suggest that they were caused by the use of an hand or forearm related reference frame.

4.3 Experiment 2

The results of Experiment 1 showed that participants made large systematic errors when asked to haptically match the orientation a reference bar. In Experiments 2 and 3 we tried to determine which stage of the matching process underlies the errors. We assumed that participants first perceive the orientation of the reference bar. This perceived orientation is then thought to be transferred to the location of the matching bar, which is produced at the matching bar location. The video recordings of Experiment 1 showed that participants first rotated the matching bar across a large angle, followed by small corrections in which the orientations of both bars were extensively probed. This observation suggests that participants strongly rely on their
perception of bar orientation. In Experiment 2 we investigated this orientation perception by asking participants to verbally report the orientation of a bar at various locations in the fronto-parallel plane. Participants were asked to imagine that the bar was the large hand of an analogue clock attached to the white-board, and to name the time on this imaginary clock.

4.3.1 Method

Participants

Twelve graduate and undergraduate students (six male) took part in the experiment. Nine of them had participated in a haptic orientation matching experiment at the department before, but none of them was familiar with the clock naming task. Two of the participants (GY and JA) were left-handed. These left-handed participants performed the task with the same hand as the right-handed participants. Five participants, who were not member of the Physics of Man Department, were paid for their participation.

Design

For each participant a list of randomly selected stimulus locations and bar orientations was generated. For each trial the stimulus location was selected at random (either upper left, upper right, bottom left, or bottom right). The first two participants received randomly selected orientations between 0 and 180 degrees. After testing these two participants we realized that participants could only report angles in an integer number times 6 degrees (corresponding to the minutes on the clock). Therefore the remaining ten participants were presented with orientations corresponding to an integer number of minutes. Each participant carried out a total of 120 trials.

Procedure

Before blindfolding the participant, the experimental task was explained visually. Participants were explained that they would be presented with bars in a randomly selected orientation of which they had to estimate the orientation. They were asked to imagine the bar was the large hand of a clock, which was attached to the white-board. Their task would be to name the time on the clock in minutes. As examples 0 (horizontal), 90 (vertical), and 42 degrees were shown by orienting a pen in the corresponding orientations, and indicating the time: 15 past, on the hour, 7 past, respectively. Participants
were free to choose how they would report the orientation. Most participants used times between on the hour and half past. Some participants used clock time names such as 45 past, or 15 before. All reported clock times were later converted to an orientation between 0 and 180 degrees.

After the instruction the participant was blindfolded and guided to the white-board. As in Experiment 1, participants were positioned such that they were standing at equal distance to the left and the right stimulus locations, at a distance of about 30 cm from the white-board. The height of the white-board was adjusted so that the participant could well reach each of the stimuli (which was, as before, at a distance of about 30 cm between the upper stimuli and the participants shoulder). On each trial the bar at the indicated location was rotated to match the orientation on the list generated for that participant. The experimenter indicated to the participant of which bar the orientation had to be estimated, by saying the positions ('upper left', 'upper right', 'bottom left', 'bottom right'). Participants were asked to inspect bars on the right with the right hand and bars on the left with the left hand. The participant verbally reported the estimated orientation in minutes. This number was written down by the experimenter. Participants could take as much time as they wanted to haptically inspect the bar orientation. Typically they would inspect the bar for 15 seconds.

The experiment was run in three sessions of 40 trials each with short breaks in between. During these breaks the participant was guided to the other side of the room. There they could take off the blindfold without seeing the setup.

4.3.2 Results

Figure 4.6 shows the presented and reported orientations of four participants (EE, HI, LO, and MI; rows) at the four test locations (columns). Several participants showed a bias in their reports for certain orientations. For example, for the bottom left bar participant EE reported orientations that were in general smaller than the presented orientation. For this subject, this pattern reverses for the bottom right orientation. Participants HI and LO show the opposite pattern: They underestimate the orientations at the bottom right position, and overestimate the orientations at the bottom left position.

Figure 4.7 shows the mean errors of each of the twelve participants. Each bar shows the mean error for a participant. Lines on top of the bars show the 95% confidence intervals. Asterisks denote the p-value found in a t-test comparing the reported and the presented orientations. A single asterisk denotes
Figure 4.6: Presented and reported orientations for each bar location. The data of four participants are shown. Presented and reported orientations are expressed as a counter-clockwise rotation with respect to the horizontal in degrees.

A p-value smaller than 0.01, and a double asterisk denotes a p-value smaller than 0.001. Although errors clearly differ across participants, a consistent pattern can be observed: Participants with an overestimation for the left positions show an underestimation for the right side and vice versa. For the top stimulus locations the correlation between the errors on the left and the errors on the right was equal to -0.635 ($p < 0.05$). For the bottom stimulus locations a correlation between left and right error of -0.791 ($p < 0.05$) was found.

As in the matching task of Experiment 1 the errors were larger for the stimuli presented at the bottom than those presented at the top of the whiteboard ($t = 7.56$, $p < 0.001$).
The errors in the clock naming task were significantly smaller than those of the matching task of Experiment 1 \((F(1, 16) = 16.618, p < 0.001;\) repeated measurements from Experiment 1 excluded from the ANOVA).

### 4.3.3 Discussion

The error pattern found in the clock naming task differed substantially across participants. However, an interesting pattern was found: The errors within each side (left and right) show a strong negative correlation. Our results extend earlier findings by Zuidhoek, Kappers, and Postma (submitted) who found small systematic errors when participants were asked to verbally report the orientation of horizontally presented bars. They found that the size of the errors depended on the orientation of the hand.

Although many systematic errors were found within participants for the
the clock naming task, the data of Experiment 2 shows that the large systematic errors found in Experiment 1 cannot be due to perception errors only. The errors in the clock naming task were significantly smaller than those in the haptic matching task. The absence of a significant mean error in Experiment 2 showed that the errors in Experiment 2 were also less consistent across participants than the errors of Experiment 1.

4.4 Experiment 3

In Experiment 3 we tested whether an incorrect production of the matching bar orientation could explain the large systematic deviations found in Experiment 1. If production errors underlie the errors of the matching errors of Experiment 1, we expect large systematic production errors which are consistent across participants and which are in the same direction as the matching errors.

4.4.1 Method

Participants

Nine participants (five male) took part in the experiment. They were all right-handed. Six of them (physics undergraduate students at Utrecht University) were naive with respect to the purpose of the experiment. These participants were paid for their participation. Three participants (PhD students at Utrecht University) had taken a part in a haptic matching experiment, but had never performed a haptic production task before.

Design

Participants were asked to produce each of four main orientations (as in the first experiment, 0, 45, 90, and 135 degrees) with each of the four bars attached to the white-board. They were asked to set bars on the left with the left hand and bars on the right with the right hand. Each orientation was produced six times. The order in which the orientations had to be produced was randomized for each participant.

Procedure

At the beginning of the experiment participants were blindfolded and guided to the white-board with the stimuli. This procedure prevented them from
seeing the experimental setup until the end of the experiment.

Before each trial the experimenter gave the bars a random orientation which was at least 10 degrees off the orientation to be produced. Then the participant was told which orientation to produce. A possible instruction would be ”set all four bars in a 45 degrees orientation”, where 0 degrees would be horizontal and 90 degrees would be vertical. Following this instruction, the participant rotated all four bars on the white-board such that they felt to be in the instructed orientation. After releasing the bar, participants were not allowed to change its orientation any more. While adjusting the orientation of the bar, the participant was not allowed to touch another bar with his other hand. Participants could freely choose the order in which they set the orientation of the bars. As in Experiment 1 the experimenter determined the orientation of the bars by looking at the protractors on the white-board.

4.4.2 Results

Participants could reproduce the instructed orientation of the bars quite accurately. Figure 4.8 shows the settings of four participants (AB, JB, MI, and WW; rows) for each of the bar positions (columns). In this figure the long lines represent the four main orientations. The shorter lines show the settings by the participant. All participants showed some systematic errors. However, these errors were not consistent across participants. Figure 4.9 shows the mean error for each participant. In this plot mean errors across orientations are shown. The mean error across participants did not differ significantly from zero ($p > 0.1$), indicating that the errors were not consistent across participants. No substantial correlation was found between the errors within the top or within the bottom row of stimuli (the respective correlations were $-0.053$ ($p > 0.1$) and $-0.50$ ($p > 0.1$)).

An oblique effect on the variable errors is present for the data in Experiment 3: T-tests on subject variances show that subjects set the horizontal and vertical bars more consistently across trials. For all four locations the variance in the settings of horizontal and vertical orientations was less than the variance in the settings of oblique orientations (all four p-values smaller than 0.05).

The errors in the production task were significantly smaller than those in the matching task of Experiment 1 ($F(1, 20) = 24.356, p < 0.001$; repeated measurements from Experiment 1 excluded from the ANOVA).
Figure 4.8: Orientations produced by four participants (AB, JB, MI, and WW). The long lines show the instructed orientations. The short lines show the produced orientations. Each column shows the settings at a different bar location.

4.4.3 Discussion

Although some participants showed systematic errors when they haptically set the orientation of bars, there were no overall systematic errors across participants. Participants were less variable in their settings of horizontal and vertical orientations than for oblique orientations. These results relate to those by Luyat et al. (2001) who used the production task to determine the subjective vertical, which is defined as the perceived orientation of gravity during body or head rotation. They asked participants to produce each of four orientations (0, 90, 45, and -45 degrees). With their head in a vertical position, they did not make systematic errors. Oblique orientations were produced with larger variability. Gentaz and colleagues (2002) asked healthy human participants and neglect patients to produce each of the four main orientations at each of two positions (20 cm to the left or 20 cm to the right of the body midline). For the vertical and the 45 degrees oblique systematic errors were made, which were absent for the horizontal and the -45 degrees
orientation. The oblique orientations were produced with larger variability than the horizontal and the vertical orientations. The errors of the healthy young participants were independent of the stimulus location. The results of Luyat et al. (2001) and Gentaz et al. (2002) correspond well with our results. The only differences concern the systematic errors Gentaz et al. found for the 45 degrees orientation and the vertical, for which no explanation could be given.

4.5 General Discussion

In the haptic orientation matching task of Experiment 1 participants made large systematic errors. We hypothesized that the matching task involved three stages: (1) the perception of the orientation of the two bars, (2) the
transfer of the perceived reference orientation to the matching location, (3) the production of the transferred orientation at the matching bar location. Experiments 2 and 3 tested the origin of the large systematic errors observed in Experiment 1. In Experiment 2 (the perception task) we asked participants to report the orientation of the bars. They were asked to tell the time, assuming that the bar was the large hand of an analogue clock. Although many systematic errors were found in the data, these errors were not consistent across participants. Also, the clock naming errors were much smaller than the matching errors of Experiment 1. In Experiment 3 (the production task) we asked participants to set each of the bars in a predefined orientation. As with the perception task in Experiment 2, some systematic errors were observed for the production task. These systematic production errors were not consistent across participants, and they were much smaller than the matching errors of Experiment 1. The combination these of results suggest that the large systematic errors in the matching task originate in the transfer of the perceived bar orientation to the location of the matching bar, and not in the perception or the production of orientations.

Results of previous haptic space experiments suggest that two frames of reference are used in haptic space tasks. One frame is linked to the external, Euclidean space. The other frame is related to the orientation of the forearm or the hand of the subject (egocentric space) (Soechting & Flanders, 1993; Kappers, 2003). In tasks in which participants instantly match the orientation of two bars (Kappers, 1999; Kappers & Koenderink, 1999; Kappers, 2002), the frame linked to the forearm or the hand is used, which results in large deviations from physical parallelity. If a delay is presented the external representation of orientation becomes more prominent, which results in smaller matching errors (Zuidhoek et al., 2003). Newport, Rabb, and Jackson (2002) showed that haptic matching errors decrease with irrelevant visual information. Matching errors were smaller when the setup and the participants hands were covered than when the participant was blindfolded. When participants have irrelevant visual information, they might rely to a larger extent on the external reference frame.

In our perception task we asked participants to imagine that the bar was the large hand of a clock attached to the white-board. This task needs to be performed in an external reference frame, since the clock times which participants had to report were defined with respect to the reference frame of an external clock. In our orientation production task participants were asked to produce orientations which also required the use of an external frame of reference. The data suggest that in the matching task egocentric
coordinates were used. Why participants consistently use this egocentric coordinate frame in the matching task is not known.

Our results show that for tasks that involve the orientation of objects, at least two haptic spaces need to be considered: An egocentric (body related) space and an allocentric (Euclidian) space. The observed errors can then be understood as a weighted combination of the two spaces. The weights would depend on the task performed and could differ across subjects. Earlier Cuijpers (2003) found a similar task dependence for the visual space. They showed that the properties of the visual space best describing the data was dependent on the experimental task.
Chapter 5

Catching oriented objects\textsuperscript{4}

5.1 Introduction

Many studies have stressed the importance of studying action and perception as two connected processes (Berthoz, 1993). A good example is the study of catching a moving object, where vision provides the information about position and orientation of the object to trigger a sequence of muscle activation patterns such that shoulder and elbow movements bring the hand to a location where the object will be just after the movement is completed.

The process of catching a moving object involves many complex subprocesses within the perception-action cycle. One important subprocess of catching movements is the preshaping of the hand (e.g., Gentilucci, 2002; Santello & Soechting, 1998). In most of the experiments in which the preshaping of the hand during catching movements was studied, participants were asked to catch a spherical object, like a ball (Savelsbergh & Whiting, 1996). When objects are not spherical but have a clear asymmetry and orientation, catching is more complicated since the orientation of the object in space has to be determined in order to catch the object properly. In this context it should be remarked that participants make systematic errors in matching the orientation of cylindrical bars or lines at different locations visually or haptically (Cuijpers et al., 2000; Hermens & Gielen, 2003; Kappers, 1999). This raises the question whether these matching errors also affect the preshaping of the hand in catching movements. Of importance here is whether vision for perception and vision for action take place in separate, independent neural pathways (Goodale & Milner, 1992). If vision for perception and vision for action make use of the same underlying representation, any errors in the percept of object orientation should be reflected in errors in catching movements to these objects.

The question to what extent vision for perception and vision for action are related, has been investigated by comparing the effect of a perceptual illusion on size estimation and grasping. For example, participants were asked to estimate the size of and to grasp the disc inside the Tichener circles illusion or the bar inside the Müller-Lyer illusion. Some studies have found that subjects could grasp objects correctly, even when the size of an object was perceived incorrectly (e.g., Haffenden & Goodale, 1998; Haffenden, Chif, & Goodale, 2000). The absence of an effect of the illusion on grasping movements in these studies suggests that vision for perception and vision for action use different neuronal pathways. Later studies have shown that a delay between the offset of the presentation of the stimulus and the onset of the grasping movement causes the peak hand aperture of the grasping move-
ment to depend on the size of the illusion (Hu, Eagleson, & Goodale, 1999; Hu & Goodale, 2000; Westwood, McEachern, & Roy, 2001). The effect of the delay has been explained by assuming that the representation for action decays quickly. After the delay the action representation of the object has decayed and the grasp is planned based on the perceptual representation.

Here we report results of experiments which investigated the effect of visual perception of object orientation on orientation adjustment of the hand in a movement, which resembled a catching movement. In the first experiment participants were asked to match the orientation of a moving line on a vertical screen by bringing a hand-held bar on a future position of the moving line in the same orientation as that of the line. They were asked to put the bar on the screen at the very moment in time when the moving line passed through a predefined interception point. This task allowed us to investigate the orientation of the hand when participants would be trying to ‘catch’ the moving line displayed on the screen. On its path towards the participant the line could disappear at one of two possible locations. If it disappeared, it could do so either just before the interception point or halfway in between starting position and interception point. The question we addressed was whether participants match the orientation of the moving line correctly by the hand-held bar, or whether they made errors corresponding to the errors in visual perception of the orientation of the line at, or before the time of disappearance.

In the first experiment we found that participants made errors when trying to match the orientation of a moving line. In the second experiment we investigated how the matching errors in the matching task were related to the errors made in a visual matching task. In particular, we tested whether participants were using the last perceived orientation of the moving line to match its orientation or that some kind of averaged perceived orientation was used.

In addition to correctly orienting the hand, a correct timing of the movement is needed for a successful catch. The timing aspect of catching movements has been studied extensively in experiments in which participants had to catch a ball (for an overview, see Savelsbergh & Whiting, 1996). In these experiments a ball was thrown towards the participant and at some time during the movement the ball was made invisible. Subjects were instructed to catch the ball, but they might fail to do so due to a lack of visual information. The number of times the ball was caught was measured as a function of the time during which the ball was visible (‘the visible period’) and the time period in which the ball was invisible (‘the occluded period’). Both the
visible and the occluded period were found to affect the percentage of balls caught (Sharp & Whiting, 1974).

So-called ‘motion extrapolation’ experiments provide additional information on the timing of catching movements. In motion extrapolation experiments a target approaching the participant becomes invisible at some point during its movement. The task of the participants is to estimate the point in time when the target arrives at a predefined target location. In general, participants could accurately predict the arrival time of the hidden object (Rosenbaum, 1975; Sokolov, Ehrenstein, Pavlova, & Cavonius, 1997; Wiener, 1962). Only when the object was hidden for more than a second, performance started to deteriorate (Lyon & Waag, 1995).

The movement data of the matching tasks in Experiments 1 and 2 show that participants made their interception movements too late. The hand tended to arrive at the interception point after the target passed through. In the third experiment we investigated whether differences in arrival time of the hand-held bar affected the accuracy of matching. Also we tested whether participants completed their arm movement to the screen after the line passed through the interception point because they could not estimate the arrival time of the hidden line correctly. Participants were asked to perform an extrapolation task. In this task they watched a line approaching them. Halfway the screen the line became invisible. The task of the participants was to press a button at the moment they thought the hidden line passed through a predefined location.

5.2 Experiment 1

In the first experiment we investigated how participants orient their hand when they have to catch an approaching line. Two catching situations were studied. In one situation the line was visible at all times throughout the movement to the participant while in the other situation it became invisible before arriving at the interception point. Participants were asked to match the orientation of the line when they thought it passed through the interception point by pressing a hand-held bar on the screen. By measuring the orientation of the bar the orientation of the hand could be determined when participants would try to ‘catch’ the line.
5.2.1 Method

Participants

Eight participants took part in the experiment. Two of them were the authors. The others were naive with respect to the purpose of the experiment. These participants were paid for their participation. All participants had normal or corrected-to-normal vision. They were all right-handed.

Apparatus

An LCD projector (Philips 4750), connected to a PC, was used for the presentation of the stimuli. The stimuli were projected within a 142 times 105 cm computer display image on a 2.5 by 2 meter vertical projection screen. Participants were asked to bring a 29 cm long bar to a predefined interception point on the screen in the same orientation as the moving line at the time that the line would pass through the interception point. The orientation of the bar was measured using an Optotrak 3020 system (Northern Digital Inc.), which measured the position of two infra-red light-emitting diodes (IREDs), attached to the bar at a distance of 20 cm. The location of the IREDs was sampled at a frequency of 50 Hz. The orientation of the bar could be measured with an accuracy better than 0.5 degrees.

The set-up used in this experiment was the same as that in a previous experiment (Hermens & Gielen, 2003), where subjects could see the edges of the projection screen. In that study, we demonstrated a clear oblique effect in the perception of slanted visual lines. Since the aim of this study was to investigate similarities in the perception and grasping of oriented lines, we did not attempt to hide the edges of the screen. The projection screen did not have any visible texture.

Stimuli

The stimuli consisted of solid lines presented on a vertical screen. The lines moved at a speed of 62 cm/s along a horizontal path towards the participant starting their movement at a location 120 cm from the left side of the image display. A predefined interception point was used which was kept constant across trials at 20 cm from the left side and 22 cm from the top of the computer display image. The starting position and the interception point location with respect to the participant is illustrated in Figure 5.1.

During its path the moving line (1) either moved across the visual display all the way from the right to the left or it disappeared (2) halfway the display
image, 75 cm from the left, or (3) just before the location at which the orientation had to be matched, 27 cm from the left of the display image. In the condition in which the line disappeared outside the screen participants could see whether the orientation of the bar matched the orientation of the moving line when they tried to cover it at the interception point. This might have provided feedback on the accuracy of the selected orientations. By having the line disappear just before the interception point the role of on-line visual feedback on the matching performance could be investigated.

All lines were presented 22 cm below the top side of the display image. At this height, the lines moved about 10 cm above eye height of the subjects.

**Design**

The orientation of the moving lines could be horizontal (0 deg), vertical (90 deg) or oblique (+45 deg or -45 deg) with +45 deg defined to be a counter-clockwise rotation of the horizontal line by 45 degrees. To stress the importance of matching the line’s orientation and not a preconceived orientation, an additional scatter of 2, 4, or 6 degrees was added to each of the main orientations. For example, for the 45 degrees orientation the orientations 39, 41, 43, 47, 49, and 51 degrees were presented. The lines could disappear at three possible locations, as described in the stimuli section. The combina-
tion of 4 main orientations, 6 orientations near these main orientations, 3 disappearance locations, and 2 repeated presentations resulted in a total of 144 trials. Each mean per participant used in the statistical analysis of the data was therefore based on 12 repeated measurements. The order of trials was randomized across participants.

**Procedure**

Participants were standing at the left of the projection screen on which the image of a moving line was projected using the LCD projector. Subjects viewed the screen from an oblique angle with the cyclopean eye at a distance of 32 cm from the screen, just in front of the left edge of the computer display image. The distance from the cyclopean eye to the intersection point of the screen straight ahead was 42 cm (see Figure 5.1).

At the start of each trial participants held the bar in their right hand near their waist. Before the line started to move, the line was shown at the starting position for 500 ms. After the line started to move participants had to bring the bar to the interception point with the proper orientation at the proper time, irrespective of whether the line continued to be visible during its movement across the screen or whether it disappeared during it’s movement to the interception point. After touching the screen with the bar the participants had to keep the bar at that location and orientation until a sound indicated the end of the trial 2 seconds after motion onset. Between the auditory signal and the beginning of the next trial there was a 2 seconds delay. The entire session took about 30 minutes.

**Data analysis**

The orientation of the bar was determined by measuring the location of two IREDs mounted on the bar at a distance of 20 cm. To obtain a good estimate of the matched orientation, the mean IRED location of the final 50 samples of each sample period were used. The orientation of the bar was computed by fitting a line through the mean locations of the two IREDs at the bar. Trials in which participants moved the bar during the final 50 samples (about 1 trial per participant), or in which one of the IREDs was not visible to the Optotrak system (about 5 trials per participant) were removed from the data analysis.

For each main orientation and each location at which the line disappeared a t-test was carried out to test whether the orientation of the hand-held bar was different from the orientation of the moving line. The significance
level for these tests was corrected for the number of tests performed using a Bonferroni correction. An analysis of variance tested the interaction between line orientation and disappearance location. Paired samples t-tests were used to determine whether the location at which the line disappeared had an effect on the size of the signed differences between bar and line orientation. Two-tailed tests were used.

5.2.2 Results and Discussion

Figure 5.2 shows the matching orientations together with the actual orientations of the moving line for each of the disappearance locations. Data of all participants have been plotted in one figure, since the pattern of results was similar across participants. Near the reference lines symbols are inserted which indicate the results of the statistical test to compare matching and reference orientations. Mean errors and standard deviations across participants are shown in Table 5.1.

![Figure 5.2](image)

Figure 5.2: Matching orientations (shorter lines) together with the reference orientations (longer lines) for the three disappearance positions of the moving line. Data from all 8 participants are shown. A single asterisk denotes a significant difference between matching and reference line orientation.

In an analysis of variance the effects of disappearance location and line orientation on signed matching errors were tested. A significant interaction effect between disappearance location and line orientation was found ($F(2,6) = 71.223, p = 0.014$).

For the disappearance location halfway the screen large systematic errors were found for the oblique orientations. The orientation of lines disappearing
Table 5.1: Mean signed errors and standard deviations across participants observed in Experiment 1 for the three disappearance locations of the moving line. An asterisk denotes a significant deviation of the mean from zero.

<table>
<thead>
<tr>
<th>Disappearance</th>
<th>0 degrees</th>
<th>90 degrees</th>
<th>45 degrees</th>
<th>-45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle</td>
<td>-1.4120</td>
<td>2.9792</td>
<td>-6.7783*</td>
<td>11.6316*</td>
</tr>
<tr>
<td></td>
<td>(2.5751)</td>
<td>(3.2205)</td>
<td>(2.7048)</td>
<td>(3.4823)</td>
</tr>
<tr>
<td>Interception point</td>
<td>-0.4514</td>
<td>1.8789</td>
<td>0.3411</td>
<td>5.0916</td>
</tr>
<tr>
<td></td>
<td>(1.3967)</td>
<td>(2.0533)</td>
<td>(2.0375)</td>
<td>(2.4741)</td>
</tr>
<tr>
<td>Outside screen</td>
<td>-1.0322</td>
<td>1.2180</td>
<td>-0.8263</td>
<td>4.3302</td>
</tr>
<tr>
<td></td>
<td>(3.3315)</td>
<td>(2.0437)</td>
<td>(1.2998)</td>
<td>(2.4787)</td>
</tr>
</tbody>
</table>

later was matched more accurately. The signed errors for oblique orientations for the disappearance location halfway the screen differed significantly from that for the other conditions (all p-values smaller than 0.001). For the orthogonal orientations no effect of disappearance location was found.

For all three conditions the size of the errors for the -45 degrees orientation was larger than that for the 45 degrees orientation (all p-values smaller than 0.035).

An additional analysis of variance tested the effects of disappearance location and line orientation on the unsigned matching errors. No significant interaction effect of disappearance location or line orientation on unsigned errors was found ($p > 0.3$). The two main effects of disappearance location and line orientation were significant (both p-values smaller than 0.01). Paired comparisons of unsigned errors of different line orientations showed that the unsigned errors of the vertical line orientation were different from those of the other line orientations (all p-values smaller than 0.01). These effects differ from those found by Hermens and Gielen (2003). In their study the two orthogonal orientations showed larger unsigned errors, while in the catching situation no different unsigned errors were found for horizontal lines and oblique lines. Paired comparisons of the unsigned errors for the different disappearance locations showed that these errors were larger for lines becoming invisible halfway the screen, compared to those becoming invisible later on during the movement (both p-values smaller than 0.01). The difference between the unsigned errors for early and late disappearing lines could reflect an effect of visual feedback.

A possible source of the observed signed errors might be the incorrect visual perception of line orientation. Hermens and Gielen (2003) have shown that participants incorrectly match the orientation of visually presented oblique
lines. If errors in visual perception were underlying the matching errors of moving lines, this might suggest that the action system is susceptible to perceptual errors. However, there might be a distinction in the kind of errors that the action system is susceptible to. All illusions used to demonstrate the existence of separate pathways for action and perception made use of information of one object relative to another object. In the Müller-Lyer illusion, for example, the size of the bar is perceived incorrectly because of the wings in the illusion. The perceptual errors in orientation perception are independent of any objects in the neighborhood of the object of which the orientation has to be estimated. Therefore, the action system might be susceptible to orientation perception errors, but not to size estimation errors.

To investigate whether there is a relation between the matching errors of Experiment 1 and visual matching errors, the size of the visual matching errors was measured in Experiment 2 to allow for a comparison. Therefore, the reference line location was varied systematically in one of the visual matching tasks of Experiment 2.

In Experiment 2 we also investigated whether orientation of the hand-held bar in Experiment 1 could be related to the orientation of the moving line at some position on its trajectory to the participant. Specifically, we investigated whether participants used an average across a fixed sampling period to match the orientation of the moving line. A possible averaging of perceived orientation might be carried out for the last perceived orientations before the disappearance of the moving line. However, another alternative might be that subjects track the moving line at the beginning of the movement and then make a saccadic eye movement to the interception point (Johansson, Westling, Backstrom, & Flanagan, 2001; Neggers & Bekkering, 2000, 2001). According to this strategy, any errors might be related to errors in the percept of line orientation near the start location of the moving line. In order to test whether participants use this strategy, we have varied the starting location of the moving line, and we expect that matching errors will be larger for lines start their movement farther away from the participant.

5.3 Experiment 2

In the first experiment we found that participants made errors when they had to match the orientation of a moving line. In the second experiment we will further explore various hypotheses regarding the origin and nature of these errors. For this purpose, the participants were asked to carry out four
different matching tasks.

Participants were tested in two visual matching tasks to compare the errors in Experiment 1 with errors in the visual perception of the orientation of a static line at different positions relative to the matching line. In addition, two additional matching tasks with moving lines were used to investigate possible strategies that participants might have used to match the orientation of the moving line in Experiment 1.

In the visual matching tasks the participants had to rotate a line ('the matching line') until it was perceived to be parallel to a reference line. The first visual matching task involved matching orientations of orthogonal (0 and 90 degrees) and oblique orientations (45, and -45 degrees). The reference line was either at the location where the line started its movement in Experiment 1 or at the location halfway the image display, where the moving line disappeared. The matching line was always at the location of the interception point of Experiment 1. If the matching errors found in Experiment 1 reflect errors in the visual perception of line orientation, the same pattern of constant and variable errors is expected as in Experiment 1.

In a second visual matching task, the participants had to match the orientation of the oblique reference lines only. To study the effect of the position of the reference line on the orientation of the matching line, the position of the reference line was varied systematically relative to the position of the matching line. The matching line was always at the interception point of Experiment 1, while the reference line was at various horizontal distances with respect to the matching line.

The third matching task was similar to that in the first experiment with the only difference that the line could move at two different velocities. The lines always became invisible halfway the screen. The speed of the line was varied to investigate whether participants might use an averaged perceived line orientation across a fixed period to match the orientation of the moving line. Since a faster moving line moves over a longer spatial interval within a fixed time period, averaging of perceived line orientations in a fixed time interval implies that perceived orientations of more distant lines are taken into account in the estimation of line orientation for higher movement velocities. If participants used a fixed time interval for averaging perceived orientation, faster moving lines are expected to result in larger matching errors.

In the fourth matching task the moving reference line, of which the orientation had to be matched, started its movement either at a short or a long distance from the participants. Earlier experiments by Johansson et al. (2001) demonstrated that participants track a moving object with their eyes
for a short time. In their experiment participants were asked to move an object to a predefined target location. Early after movement onset participants moved their eyes from the moving object to the target location. By varying the distance at which the line started its movement we investigated whether participants looked away from the moving line early after movement onset. If participants of Experiment 1 looked away from the moving line early after the line’s movement onset, errors are expected to be larger for lines starting their movement at a long distance than for lines starting at a short distance.

5.3.1 Method

Participants

The number of participants in the four matching tasks was 6, 6, 7, and 6, respectively. The two authors (FH and SG) participated in all four matching tasks. The other participants were naive with respect to the purpose of the experiment. The participants, who were not members of the department of Biophysics, were paid for taking part. All participants had normal or corrected-to-normal vision.

Apparatus

For stimulus presentation the same PC and LCD projector were used as in Experiment 1. In the visual matching tasks the orientation of one of the projected lines (the ‘matching line’) could be adjusted using a computer keyboard. The equipment used for matching the orientation of the moving lines was identical to that used in Experiment 1.

Stimuli

In all matching tasks computer-generated lines served as stimuli. The lines used in the visual matching tasks consisted of seven dots each at 13 mm distance within the 142 by 105 cm display image, plotted in white on a black background. Because participants could spend as much time as they wanted in the visual matching task, seven dots were used instead of a solid line. A solid line would have allowed participants to estimate its orientation by looking at the staircase pattern within the line, which originated from the finite resolution of the visual display in graphics mode.

The group of participants performing the first of the two visual matching tasks were presented with a reference line either in the upper right part of
the screen with the center at 122 cm from the left side of the display image, or at the middle of the screen 67 cm from the left side. The matching line was always presented in the upper left part of the screen with its center at the interception point in Experiment 1, which was at the same height as the reference line, at a distance of 20 cm from the left side of the display image.

In the second visual matching task the reference line could appear at one of eight possible locations, namely at 44, 55, 67, 78, 89, 100, 111, or 122 cm from the left of the display image. The orientation of this reference line had to be matched by rotating the matching line, which was always presented at the upper left part of the screen at the interception point in Experiment 1 with its center 20 cm from the left side.

In the third matching task the paradigm was the same as that in Experiment 1. The only difference was that the line could move at a low speed (31 cm/s) or at a high speed (62 cm/s, which was the same as that in Experiment 1). The line started its movement 122 cm from the left side of the display image and it always disappeared halfway the computer display (67 cm from the left side of the display image).

In the fourth matching task the moving lines were visible in two different parts of the visual display. Half of the lines started their movement 106 cm from left side of the display image, while the other half started at 75 cm from the left. All lines disappeared when their center was at 44 cm from the left of the display image.

The lines in the four matching tasks were all presented at the same height as in Experiment 1, about 10 cm above eye height.

Design

For the first visual matching task four main orientations of the reference line (45, -45, 0, and 90 degrees with respect to the horizontal) were used. In the other tasks only the two oblique orientations (45 and -45 degrees) were used.

For the visual matching tasks (the first two tasks) an additional scatter of 2 or 4 degrees was added to the four main orientations. For example, for the 45 degrees orientation, the reference line could be presented with equal probability at an orientation of 41, 43, 45, 47, or 49 degrees. For the matching tasks with moving lines the main orientation itself was not presented. Instead orientations plus or minus 2, 4, or 6 degrees relative to the main orientation were used. The participants were told that some scatter had been added to the orientation of the line, so that it would be important to align the orientation of the matching line with that of the reference line,
instead of, for example, matching some preconceived orientation relative to external cues, such as gravity or the edges of the screen.

For the visual matching tasks each combination of main orientation and reference line location was presented ten times to each participant. In the other two matching tasks, each condition was tested 12 times. The order of the trials was randomized for each participant.

Procedure

The participants performing the visual matching task were seated in a chair at the left side of the projection screen at the same location where participants were standing in Experiment 1. The height of the chair was adjusted such that the participants were viewing the screen at about the same height as they would be viewing it when they were standing.

At the beginning of each visual matching trial two lines appeared on the screen, each consisting of seven dots, and the participant was asked to rotate the matching line using the computer keyboard such that its orientation matched that of the reference line. The orientation of the matching line could be adjusted in steps of 2, 0.5, or 0.1 degrees. The participant pressed a button when satisfied with the selected orientation. After the button was pressed the screen was cleared and after a 1000 ms inter-trial interval two new lines appeared on the screen.

Participants matching the orientations of moving lines carried out the same task as the participants of Experiment 1. They pressed a hand-held bar on the predefined interception point on the screen at the moment they thought the invisible line would pass through the interception point. They tried to hold the bar in the same orientation as the moving line.

Data Analysis

To test for systematic errors in the visual matching tasks a signed error was computed as the difference between the orientation of the reference line and that of the matching line. The signed error for the matching task with moving lines was computed by taking the difference between the orientation of the hand-held bar and the orientation of the moving line. Statistical tests using means per participant were used to test whether the signed errors were different from zero. For the first visual matching tasks, where 8 paired t-tests were carried out, a Bonferroni correction was applied to the significance level.
Table 5.2: Mean signed errors and standard deviations across participants found for the visual matching task with two main reference line locations. Asterisks denote a significant difference between matching and reference line orientation.

<table>
<thead>
<tr>
<th>Reference location</th>
<th>0 degrees</th>
<th>90 degrees</th>
<th>45 degrees</th>
<th>-45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle of the screen</td>
<td>0.1250</td>
<td>0.1767</td>
<td>-0.6650</td>
<td>1.1000</td>
</tr>
<tr>
<td></td>
<td>(0.3781)</td>
<td>(1.0320)</td>
<td>(2.5447)</td>
<td>(5.3240)</td>
</tr>
<tr>
<td>Right of the screen</td>
<td>-0.1083</td>
<td>-0.2380</td>
<td>-4.7117</td>
<td>7.1161*</td>
</tr>
<tr>
<td></td>
<td>(0.5899)</td>
<td>(1.2825)</td>
<td>(4.0870)</td>
<td>(2.7429)</td>
</tr>
</tbody>
</table>

5.3.2 Results

Figure 5.3 shows the orientations of the reference lines (longer lines) and corresponding matching lines (shorter lines) for the first visual matching task. The orientations at the left and right side of figure 5.3 correspond to the matching orientations for reference lines at the middle (67 cm to the left of the edge of the computer display image) and upper right side (122 cm from the edge of the computer display image) of the computer visual display, respectively. Since similar results were obtained for each of the participants, data from all participants were plotted in one figure. Tilde and asterisk symbols in the plot show the outcomes of statistical tests using means per participants. A tilde-sign denotes a non-significant difference between the reference and matching orientations. A single asterisk refers to a difference at a significance level of 0.05.

Mean signed errors and their standard deviations for the first visual matching task are listed in Table 5.2. An analysis of variance tested the effects of reference line location and line orientation on signed errors. A significant interaction effect between reference line location and orientation was found ($p < 0.05$).

As in Experiment 1, small mean errors were found for the 0 and 90 degrees orientations and larger errors were observed for the -45 and 45 degrees orientations. Only for -45 degrees orientations at the upper right position significant errors were found.

The errors for the oblique orientations in Experiment 1 and the visual matching task were compared using an ANOVA. Data from participants who took part in both matching experiments were excluded for this test (the effect of task was tested between subjects, the effect of line orientation was tested within subjects). The errors for the middle disappearance location of Experiment 1 and those for the upper right matching location of the visual
matching task were compared. A significant interaction effect was found between the orientation of the reference line (+45 deg or -45 deg) and the matching task (‘catching’ vs visual matching). Tests of simple effects showed that there was no effect of matching task for the -45 degrees orientation ($p = 0.224$), while the errors for the +45 degrees orientation were significantly different for the two matching tasks ($p = 0.001$).

A paired samples t-test demonstrated that the effect of reference location was significant for the two oblique orientations (both $p$-values smaller than 0.006). Larger errors were found for more distant reference line locations. This result suggests that errors increase with increasing distance between the matching and the reference line.
In the second visual matching task the influence of the distance between the two lines was investigated in more detail. This was done by systematically varying the horizontal position of the reference line while keeping the matching line at the same position.

The results of the second visual matching task are shown in Figure 5.4. In this figure unsigned mean differences between the orientation of the matching and the reference line are shown for each participant. The means across participants are shown in the last subplot of the figure. Unsigned errors are shown to allow for a comparison of the size of the errors for the two types of oblique lines (-45 and +45 degrees). If participants performed the matching task solely on the basis of the orientation of the retinal image of the lines the size of the errors was expected to be equal for both types of oblique lines. A t-test using means per distance to the reference line determined the significance of the mean error difference for the -45 and the +45 degrees orientation. For three of the seven participants the difference in the size of the errors for the -45 and the +45 degrees orientation was significant ($p < 0.005$). The plots of Figure 5.4 show that errors increase with the distance of the reference line towards the observer.

In Experiment 1 the participants made significant errors in matching for the reference line, which disappeared at a distance of 75 cm from the left side of the display image. A comparison of the data in Figures 1 and 4 shows that the errors for the condition, in which the reference line disappeared halfway the screen in Experiment 1, are considerably larger than that at the corresponding distance in Figure 4. The mean error for the ‘catching’ task was near 8 degrees, while the mean visual matching error for a reference line at a distance of 75 cm was close to 3 degrees. This means that participants of Experiment 1 did not use the final perceived orientation of the moving line to match its orientation.

In two subsequent matching experiments we tested two other possible strategies which subjects of Experiment 1 could have used. First a strategy in which participants based their matching orientations on some time-averaged perceived orientation of the moving line. If participants used such a time-averaged perceived orientation the speed of the moving line was expected to have an effect on matching accuracy. Figure 5.5 shows the mean errors for each participant for the two line speeds. Mean signed errors and standard deviations are shown in Table 5.3. In this table the results of statistical tests are included. These tests determined the significance of the difference between the actual orientation of the moving line and the orientation of the bar held by the participants.
An ANOVA of the signed errors with line speed and line orientation as factors demonstrated an effect of line orientation \((F(1, 5) = 30.4, \ p = 0.03)\), but no significant interaction effect between line speed and line orientation. Also no significant main effect of line orientation was found \((p > 0.4)\).

The second matching task with moving lines investigated whether participants estimate the orientation of the moving line from the first part of the movement. A group of participants matched the orientation of moving lines starting at two different starting positions. Mean errors for each participant and for each starting position of the moving line are shown in Figure 5.6. The mean errors and their standard deviations are listed in Table 5.4. Within the -45 degrees orientation the mean error was larger for almost each participant when the line started its movement at a more distant position. An analysis of variance tested the effects of starting location and line orienta-
Figure 5.5: Mean difference between the orientation of the moving line and the hand-held bar. The mean differences for the moving lines with an orientation of -45 degrees are shown in the left panel, and those for the lines with an orientation +45 degrees are shown in the right panel. The black bars show the mean difference for the slowly moving lines, and the white bars for the bars moving at a high speed.

Table 5.3: Mean signed errors and standard deviations across participants for the matching task with lines moving at one of two possible speeds. In the plot a tilde-sign shows that the signed errors were not significantly different from zero. An asterisk represents a significant difference at a significance level of 0.05.

<table>
<thead>
<tr>
<th>Speed</th>
<th>45 degrees</th>
<th>-45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low speed</td>
<td>-8.8117* (3.9986)</td>
<td>5.9133* (2.8946)</td>
</tr>
<tr>
<td>High speed</td>
<td>-9.6833* (5.1280)</td>
<td>5.9283* (3.7548)</td>
</tr>
</tbody>
</table>

5.3.3 Discussion

In the first visual matching task, in which participants matched both orthogonal and oblique orientations, a qualitatively similar pattern of results was obtained as in the matching task of Experiment 1. No systematic errors were found for orthogonal line orientations both for the catching and the visual
matching task, while for the two oblique orientations systematic effects were found in both tasks. In the matching task the orientation of the hand-held bar was tilted further towards the vertical when the line disappeared at a more distant location. In the visual matching task the orientation of the matching line was set to a more vertical orientation when the reference line was presented at a larger distance. The qualitative similarity of the outcomes of the visual matching task with static lines and the haptic matching task with moving lines suggest that participants selected the orientation of the hand-held bar on the basis of the perceived orientation of the moving line.

When reference line orientation was varied systematically, a sigmoidal relationship was found between perceived orientation and distance towards the line. The function of perceived error appears to be sigmoidal with the
steepest increase in error at a distance of about 80 cm from the left of the display image.

It is well known that geometric distortion causes deviations between line orientation in space and orientation of the line on the retina. In order to investigate the effect of geometric distortion on visual matching errors, we calculated the expected retinal image of two lines presented on a frontal plane to see whether participants perform the matching task using the orientations in the retinal image only. For the computations the lines were assumed to be presented at eye height. The distance from the eye lens to the retina was set to 1 cm, although any other value could have been chosen (e.g., Pizlo, 1994). The predicted error as a function of the distance of the reference line is shown in Figure 5.7.

Figure 5.7: Predicted absolute mean errors for the -45 and the 45 degrees orientation, if participants use the orientations on the retinal image to match the orientations of the line.

Overall, participants made smaller errors than those predicted by perspective distortion. This means that participants could, in part, correct for the effects of perspective distortion.

One might argue that the matching tasks in Experiment 1 and 2 were ambiguous, since participants might have thought that the lines on the retina should be matched in orientation. However, some participants who took part in two experimental tasks were presented with the systematic errors they made in the first of the two tasks. No differences were found between the
errors of participants who were new to the task and participants who knew about the systematic errors they made in the previous task. This suggests that participants could not correct for the retinal distortion even when they knew that such a distortion occurred.

The matching task in which the speed of the moving lines was varied demonstrated that participants did not use a fixed time interval to average the perceived orientation of the reference line. Possibly, a small effect of line speed was present in the data, which might not have become obvious because of a lack of statistical power. Still, if an effect of line speed was actually present in the data, its direction was not consistent across participants.

Instead, it is more likely that participants looked away from the moving line early after its movement onset as demonstrated by the significant effect of the starting position of the moving line. Such a viewing strategy has been shown to occur in an experiment by Johansson et al. (2001). Participants, who were instructed to move a bar to a target location, did not follow the hand with their eyes all the way to the target location. Instead they tracked the object for a short time and then made a saccade to the target location early after movement onset. The results of our study suggest that participants follow a similar strategy as that reported by Johansson et al. (2001). The orientation errors were related to the errors in the perceived orientation early after movement onset.

5.4 Experiment 3

Participants of Experiments 1 and 2 were asked to press the hand-held bar at the screen at the very moment they thought the hidden line passed through the interception point. The moment at which the movement of the bar to the screen ended could be estimated from the movement data of Experiments 1 and 2. In Figure 5.8 the mean time between the disappearance of the line and the end of the interception movement is plotted. The left panel of Figure 5.8 shows the timing data of the fourth matching task of Experiment 2. In this matching task the lines were invisible across a distance of 24 cm. In half of the trials the lines were visible across a long distance, and in the other half of the trials across a short distance. In the right panel the timing data of Experiment 1 are shown. Only the data of the lines invisible across a distance of 55 cm are shown, because the sampling periods (which started after the disappearance of the line) of the other two conditions were too short to estimate the end of the matching movement accurately. The horizontal
lines in Figure 5.8 indicate when the line actually reached the interception point. Since the lines in both experiments moved at the same speed, the arrival of the hidden line depends on the hidden distance only. Figure 5.8 demonstrates that in general participants ended their movement after the line had passed the interception point.

Figure 5.8: Mean duration of the interval between the disappearance of the line and the end of the matching movement for each of the participants carrying out the fourth matching task of Experiment 2 (left panel) and of Experiment 1 (right panel). In the left panel the white bars show the time when the line started its movement at the near starting position. The black bars show the times for the lines starting at the distant starting position.

The important issue at stake is whether the errors in the timing of the movement affected the accuracy with which the orientation of the line was matched. In experiments in which participants were asked to grasp an object within a visual illusion, the effect of the illusion was found to increase with the delay between stimulus presentation and the onset of the grasping movement (Westwood et al., 2001). To investigate whether there was a relationship between the timing error and the orientation matching error, the correlation between the two errors was computed for each participant of Experiment 1 and of the fourth matching task in Experiment 2. Across participants the correlations for both matching tasks were close to zero. For Experiment 1 the mean correlation was -0.0839 and for Experiment 2 the mean correlation was -0.0471, implying there was no relationship between timing errors and orientation matching errors. A previous study showed that the duration of the delay did affect the effect of an illusion on grasping (Westwood et al., 2001). We didn’t find a correlation between the duration until the end of the movement and the orientation error. This is in favor of the hypothesis that
representations for action and perception of line orientation are the same.

Participants could have ended their interception movements too late because they overestimated the time the line needed to arrive at the interception point. A motion extrapolation experiment was carried out to investigate whether an overestimation of the hidden interval of the line caused the late interception movements. In this motion extrapolation experiment participants were presented with the same moving lines as in the first experiment. Their task was to press a button at the moment they thought the hidden line passed through a predefined interception point. If participants would overestimate the hidden interval, they would press the button too late.

5.4.1 Method

Participants

Six participants took part in the experiment. Two of them were the authors. The other participants (students at the university of Nijmegen) were paid for their participation.

Apparatus

The same equipment was used as in Experiment 1. A button box connected to the parallel port of the computer was used to measure response times. The button box allowed response times to be measured with an accuracy better than 1 ms.

Stimuli

The same lines as in Experiment 1 were used. They moved at a speed of either 31 or 62 cm/s. Each line started to move at one of three starting positions, namely 129 cm, 124 cm, or 120 cm from the left side of the display image. The lines became invisible either 71 cm, 77 cm, or 82 cm from the left of the display image. The starting and disappearance locations were varied to make sure that people would not base their responses on estimates of the interval from the start position to the interception point or the interval from the disappearance location to the interception point. Lines were oriented at 0, 90, 45, and -45 degrees with respect to the horizontal, as in Experiment 1. No scatter was added to each main orientation.
Design

The combination of two speeds, three starting positions, three disappearance positions, and four orientations resulted in a total of 72 trials. Each combination was presented twice resulting in a total of 144 trials. Participants needed about 25 minutes to complete the experiment.

Procedure

At the start of each trial the line appeared at its starting position where it stood still for 500 ms. Then it started moving towards the participant either at a slow or a fast speed. When the center of the line arrived at the disappearance position, it became invisible. Participants were asked to press the button on the button box when they thought the line (which was invisible at that moment) passed through the predefined interception point. After they had pressed the button, they received feedback by a cross sign presented at the actual location of the line at the moment the button was pressed. The feedback was presented for 1000 ms, followed by an intertrial interval of 2 seconds. Each participant received 10 practice trials to get familiar with the task.

5.4.2 Results

First the data were inspected for practice effects. If performance would improve during the experiment, negative correlations were expected between trial number and signed error (the distance between the target location and the location of the line at button press). A mean correlation across participants between trial number and signed error of -0.0917 indicated that performance did not improve considerably during the course of the experiment. The very low correlation also means that participants did not use the feedback to improve the performance during the experiment.

In addition, autocorrelations of signed and unsigned errors were computed to check for inter-trial effects. Maybe participants would try harder to correctly predict the correct location of the line after a trial with a large error. This would then result in a high negative autocorrelation for unsigned errors. If participants would use the strategy to press the button later on a trial after a trial in which they pressed too early and visa versa, a positive autocorrelation was expected for the signed errors. The average autocorrelation for unsigned errors was equal to 0.1417, and that for the signed errors equal to -0.0617. The low correlation values show that there were no intertrial effects.
Table 5.5: Mean signed errors in cm (computed as the difference between actual location at button press and target location) and their standard deviations. Positive errors represent too early button presses.

<table>
<thead>
<tr>
<th>Speed</th>
<th>0 degrees</th>
<th>90 degrees</th>
<th>45 degrees</th>
<th>-45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>4.1886</td>
<td>4.1210</td>
<td>6.2062</td>
<td>3.5559</td>
</tr>
<tr>
<td></td>
<td>(3.2563)</td>
<td>(3.3336)</td>
<td>(4.9190)</td>
<td>(2.7449)</td>
</tr>
<tr>
<td>Fast</td>
<td>-0.7152</td>
<td>0.7170</td>
<td>-0.5447</td>
<td>0.02699</td>
</tr>
<tr>
<td></td>
<td>(2.9619)</td>
<td>(3.9526)</td>
<td>(3.1830)</td>
<td>(3.7391)</td>
</tr>
</tbody>
</table>

A repeated measure ANOVA tested the effects of speed and orientation on the extrapolation accuracy. A significant effect of line speed was found \((F(1, 5) = 8.070, p = 0.036)\). Line orientation did not have an effect \((F(3, 3) = 0.145, p = 0.926)\). The interaction between speed and orientation was not significant \((F(3, 3) = 0.683, p = 0.619)\).

In Table 5.5 mean signed errors for each of the movement speeds and line orientations are shown.

### 5.4.3 Discussion

Participants could reasonably well estimate the moment at which the line passed through the interception point. For the slowly moving lines participants pressed the button too early, underestimating the duration of the hidden interval. This means that participants of Experiments 1 and 2 did not end their movements too late because they could not estimate when the hidden line arrived at the interception point. Instead, they might have focused on matching the orientation of the hidden line which decreased the accuracy of the timing of the movements.

No effect of orientation of the line was found on extrapolation accuracy. This means that participants could correctly extrapolate the movement of the center of the line, ignoring the remainder of the line. Earlier Castet et al. (1993) found an effect of line orientation on speed estimates. We did not find an effect of line orientation on extrapolation accuracy. The long interval across which our lines were visible, might explain the difference in the effects of line orientation in the two experiments (Castet et al., 1993).

A significant effect of line speed on extrapolation accuracy was found. Participants mainly underestimated the time that the line needed to reach the target location when the line was moving at a low speed. Earlier Lyon and Waag (1995) showed that extrapolation accuracy decreased with the invisible
period when lines were invisible for more than a second. In our experiment the slowly moving line was invisible for more than a second, which might explain the effect of line speed that we found.

5.5 Conclusions

When participants had to match the orientation of an approaching line they made systematic errors. The errors became larger when the line disappeared farther away from the participant. Qualitatively the errors matched those made in a visual matching task (Experiment 2). The results in our study indicate similar findings for errors in matching oblique lines in a perceptual (visual) matching task and in an active matching task, where subjects match the orientation of a bar to that of a moving line by arm movements. The similar pattern of errors in these two conditions might be interpreted as evidence against the hypothesis of two different pathways for “vision for perception” and “vision for action”. In our study subjects had to match the orientation of a single line. In most studies on differences in “vision for perception” and “vision for action” responses were studied to stimuli in different contexts, for example for the Tichener circles illusion, where the size of the inner circle surrounded by other circles with different diameters had to be estimated. Whether or not context has an effect on differences in “vision for perception” and “vision for action” is not clear and might be a topic for further research.

The visual matching data suggested that participants did not use the final perceived orientation of the moving line to match its orientation. No evidence was found that participants used a fixed sampling time interval, since no differences matching between errors for slowly and fast moving lines were found. Instead, a small but significant effect was found of the horizontal position at which the movement started. This effect is consistent with the assumption that participants looked away from the moving line early after it started its movement, since errors in the percept of line orientation increase with the distance between the matching line and the reference line.

Although participants were instructed to match the orientation of the hidden line at the moment at which it passed through the interception point, they ended their interception movements too late. The results of a motion extrapolation experiment showed that participants could well estimate the duration of the hidden interval. The timing errors in the matching experiments might have occurred because participants focused on correctly orient-
ing the bar. Important is that the timing errors were not related to the size of the orientation matching errors. This means that the duration between stimulus presentation and matching did not affect the size of the matching errors.
Bibliography


424.
Summary

This thesis describes four studies in which we investigated perception and movement planning needed for oriented object grasping. In Chapter 2 we compare model predictions with experimental data concerning reaching movements. In Chapters 3 through 5 we describe experiments designed to investigate visual and haptic space. Chapter 5 also deals with how incorrect perception of object orientation affects object interception. The next sections provide a summary of each study separately.

Chapter 2

Various models have been proposed in the literature to explain the control of human arm movements. To make a quantitative comparison between the predictions of various models, we tested subjects for movements to targets on a vertical screen in various conditions. Subjects were asked to move directly from one target to another, or to move by a via point, at various movement velocities and in a condition with a weight of 0.6 kg attached to the forearm. This set of experimental data was used for comparison with the predictions by various posture-based and trajectory-based models on 3-D movement planning and control. Small, but significant effects of starting position and path towards the target were found on the torsion of the arm at the end of the movement. No effects of movement velocity and weight attached to the forearm were found. The experimental results differed significantly from the predictions by any of the models considered. Of the models considered Donders’ law gave the best fit to the experimental data. Our data indicate that future tests of models for motor control (1) should compare the predictions of not just one, but several models to a data set, and (2) that not only planar, but rather 3D movements should be included in such a comparison.

Chapter 3

In this study we investigated the perception and production of line orientations in a vertical plane. Previous studies have shown that systematic errors are made when participants have to match oblique orientations visually and haptically. Differences in the setup for visual and haptic matching did not allow for a quantitative comparison of the errors. To investigate whether matching errors are the same for different modalities we asked participants
to match a visually presented orientation visually, haptically with visual feedback, and haptically without visual feedback. The matching errors were the same in all three matching conditions. Horizontal and vertical orientations were matched correctly, but systematic errors were made for the oblique orientations. The errors depended on the viewing position from which the stimuli were seen, and on the distance of the stimulus to the observer.

Chapter 4

Chapter 3 described a study in which we compared the structure of visual and haptic space. In Chapter 4 three experiments are described in which we investigated the structure of fronto-parallel haptic space in more detail. In the first experiment we asked participants to rotate a matching bar such that it felt parallel to the reference bar. The bars could be at various positions in the fronto-parallel plane. Large systematic errors were observed. Orientations that were perceived to be parallel were not physically parallel. In two subsequent experiments we investigated the origin of these errors. In Experiment 2 we asked participants to verbally report the orientation of haptically presented bars. In this task participants made errors which were considerably smaller than those made in Experiment 1. In Experiment 3 we asked participants to set bars in a verbally instructed orientation. Participants made errors which were significantly smaller than those observed in Experiment 1. The data suggest that the errors in the matching task originate from the transfer of the reference orientation to the matching bar position.

Chapter 5

The experiments described in Chapters 3 and 4 showed that people do not always perceive object orientations correctly. In Chapter 5 we investigated how incorrect orientation perception affects object interception. We did this by investigating how participants match the orientation of a line, which moves on a vertical screen towards the subject. On its path to the participant, the line could disappear at several positions. Participants were instructed to put a bar on a predefined interception point on the screen, such that the bar touched the screen with the same orientation as the moving line at the very moment when the line passed through the interception point or (in case of line disappearance) when the hidden line would pass through the interception point (like in catching). Participants made significant errors for oblique orientations, but not for vertical and horizontal orientations of the
moving line. These errors were small or absent when the moving line was visible all the way along its path on the screen. However, these errors became larger when the line disappeared farther away from the interception point. In a second experiment we tested whether these errors could be related to errors in visual perception of line orientation. The results demonstrate that errors in matching of the bar do not correspond to the last perceived orientation of the line, but rather to the perceived orientation of the moving line near the begin of the movement path. This is compatible to earlier observations that participants shortly track a moving target and then make a saccadic eye movement to the interception point.
**Samenvatting**

In vier series experimenten hebben we de waarneming en bewegingsplanning onderzocht die voorafgaan aan het oppakken van objecten met een bepaalde oriëntatie. In hoofdstuk 2 vergelijken we voorspellingen van modellen met experimentele gegevens uit een bewegingsexperiment. Hoofdstukken 3 tot en met 5 beschrijven experimenten waarin de structuur van visuele en haptische ruimte werd onderzocht. Hoofdstuk 5 gaat ook in op de invloed van een foutieve waarneming van object oriëntatie op het vangen van een object. We geven nu een samenvatting van elke reeks experimenten afzonderlijk.

**Hoofdstuk 2**

In de literatuur zijn verschillende modellen gepresenteerd die de planning van menselijke armbewegingen proberen te beschrijven. Om een kwantitatieve vergelijking te kunnen maken tussen de voorspellingen van verschillende modellen, hebben we proefpersonen gevraagd bewegingen naar doelen op een vertikaal scherm uit te voeren in verschillende condities. We vroegen onze proefpersonen van het ene doel naar het andere te bewegen in een directe beweging, of tijdens de beweging via een tussenpunt te gaan. Proefpersonen voerden de bewegingen zowel snel als langzaam uit. Daarnaast voerden ze ook de bewegingen uit terwijl er een gewicht van 0.6 kg aan de onderarm was bevestigd. De gegevens die op deze manier werden verkregen, zijn vergeleken met de voorspellingen van verschillende houding-gebaseerde en pad-gebaseerde modellen voor het plannen en uitvoeren bewegingen in drie dimensies. Er werden kleine, maar significante effecten van de startpositie en het pad naar het doel op de houding van de bovenarm aan het eind van de beweging gevonden. We vonden geen effecten van de bewegingsnelheid of het gewicht dat aan de onderarm was bevestigd. De bewegingsgegevens verschillen significant van de voorspellingen van de beschouwde modellen. Van de onderzochte modellen leverde Donders’ wet de beste beschrijving van de bewegingsgegevens. Onze gegevens laten zien dat in toekomstig onderzoek naar bewegingsplanning (1) gegeken moet worden naar voorspellingen van verschillende modellen in relatie tot één enkele gegevensset, en (2) dat niet alleen bewegingen binnen een vlak maar ook bewegingen in de drie-dimensionale ruimte onderzocht moeten worden.
Hoofdstuk 3

In het onderzoek voor hoofdstuk 3 hebben we gekeken naar het reproduceren van oriëntaties van lijnen in een vertikaal vlak. Eerder onderzoek heeft aangetoond dat proefpersonen systematische fouten maken als ze gevraagd worden schuine oriëntaties visueel en haptisch te matchen. Verschillen in de opstelling lieten daarbij niet toe om de grootte van de fouten in visueel en haptisch matchen kwantitatief met elkaar te vergelijken. Om de fouten in de twee modaliteiten met elkaar te vergelijken hebben we proefpersonen gevraagd visueel aangeboden oriëntaties zowel visueel, haptisch met visuele terugkoppeling als haptisch zonder visuele terugkoppeling te matchen. Daarbij vonden we dat de systematische fouten vergelijkbaar waren in alle drie de condities. Horizontale en verticale lijnen werden correct gereproduceerd, maar systematische fouten werden gevonden voor de schuine oriëntaties. De fouten waren afhankelijk van het gezichtspunt waar vandaan de lijnen werden gezien en van de afstand van de lijnen tot de waarnemer.

Hoofdstuk 4

In hoofdstuk 3 beschreven we onderzoek waarin we de structuur van de visuele en de haptische ruimte met elkaar vergeleken. In hoofdstuk 4 worden drie experimenten beschreven waarin we de haptische ruimte van het fronto-parallele vlak nauwkeuriger hebben onderzocht. In het eerste experiment vroegen we onze proefpersonen om een staafje zo te draaien dat dit parallel voelde aan het voorbeeldstaafje. De staafjes werden aangeboden op verschillende locaties in het fronto-parallele vlak. Proefpersonen maakten bij deze taak grote systematische fouten. Oriëntaties die parallel werden beoordeeld, waren in werkelijkheid ver van parallel. In het tweede experiment vroegen we onze proefpersonen de oriëntatie van staafjes te benoemen. Hierbij werden veel kleinere fouten gemaakt vergelijk met de fouten uit het eerste experiment. In het derde en laatste experiment vroegen we aan de proefpersonen om de staafjes in een bepaalde oriëntatie te zetten. Ook hierbij werden veel minder grote fouten gemaakt dan in het eerste experiment. De onderzoeksgespreks gegevens kunnen verklaard worden door aan te nemen dat de fouten in de gelijkzettaak van het eerste experiment veroorzaakt worden tijdens het verplaatsen van de voorbeeldoriëntatie naar de testlocatie.
Hoofdstuk 5

De experimenten die we in hoofdstukken 3 en 4 hebben beschreven hebben laten zien dat proefpersonen de oriëntaties van objecten niet altijd correct waarnemen. In hoofdstuk 5 onderzoeken we hoe de fouten in de waarneming van oriëntatie het onderscheiden van objecten kunnen beïnvloeden. Dit werd onderzocht door proefpersonen de oriëntatie van een lijn, die naar ze toe bewoog op een verticaal scherm, te laten matchen. Tijdens de beweging naar de proefpersoon toe kon de lijn onzichtbaar worden. Proefpersonen moesten een balkje op een onderscheppingspunt leggen in de oriëntatie waarin zij dachten dat de lijn zich bewoog precies op het moment dat de (dan eventueel onzichtbare) lijn op het onderscheppingspunt was aangekomen (zoals in een vangbeweging). Voor schuine oriëntaties kozen proefpersonen balkoriëntaties die duidelijk afwaken van de werkelijke oriëntatie van de bewegende lijn. Deze fouten waren praktisch afwezig voor horizontale en verticale lijnen en voor lijnen die zichtbaar bleven tot aan het onderscheppingspunt. De fouten werden groter als de lijn verder weg van de proefpersoon onzichtbaar werd. In een tweede experiment onderzochten we of de gemaakte fouten gerelateerd waren aan de laatst waargenomen oriëntatie van de lijn of aan de waargenomen oriëntatie aan het begin van de beweging. De resultaten van dit tweede experiment laten zien dat de onderscheppfouten niet overeenkomen met de laatst waargenomen oriëntatie van de lijn. Eerder zijn de fouten in het eerste experiment gerelateerd aan de waargenomen oriëntatie van de lijn aan het begin van de beweging. Dit stemt overeen met waarnemingen van oogbewegingen van proefpersonen die een bewegend doel volgden. Zij volgden het doel maar kort met hun ogen om dan een oogbeweging naar het onderscheppingspunt te maken.
Publications


Curriculum Vitae

I studied Physics, ‘Language, Speech, and Computer Science’, and Cognitive Science at the University in Nijmegen. In 2000 I earned my MSc degree in Cognitive Science with a thesis on human speech production describing experiments performed at the Max Planck Institute of Psycholinguistics in Nijmegen under supervision of Dr. A.S. Meyer, Prof. W.J.M. Levelt and Dr. N.O. Schiller. I went to Oldenburg, Germany for a year to work in the lab of Prof. H. Colonius. During that year I also worked on a research project on visual masking with Prof. G. Francis (Purdue University, USA). In 2001 I started my PhD project with Prof. C.C.A.M. Gielen, which resulted in this thesis. During my PhD project I also participated in research projects in the labs of Prof. A.M.L. Kappers (Utrecht University), and Prof. D.A. Rosenbaum (Penn State University, USA). From October 2004 I am in Prof. M.H. Herzog’s psychophysics lab at the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland.