Multiple Reference Frames in Haptic Spatial Processing

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Multiple Reference Frames in Haptic Spatial Processing

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Chapter 1
Introduction

Introduction

Our everyday interactions with the environment provide us with a continuous stimulation of all our sensory systems. This sensory flow is of vital importance since it allows us to evaluate the relationship between ourselves and the environment in order to move and act within this same environment, and to interact with other beings and objects that are part of it. Information is gathered through different highly specialized senses, each of which have specific structural and functional properties allowing the transduction of specific physical signals into nervous signals that are processed into meaningful information. The focus of this thesis will be directed to the sense of touch, the haptic sense, with the occasional foray into the visual sense. Attention will be given especially to the processes that are involved in haptic perception of spatial relations. More specifically, I will address the issue of how human beings perceive the relations between objects in near space that is within easy reach of the two arms of a stationary person. My main interest is to define a general framework for haptic spatial processing and for this purpose I will propose that haptic spatial processing is a product of multiple interacting reference frames.

In this introductory chapter, some general information about haptic perception will be provided with an emphasis on spatial processing and the role that reference frames have in the acquisition of spatial information. Finally, an overview of the conducted studies will introduce the reader to the rest of the thesis.

Haptic Spatial Processing

Usually, the term haptic perception relates to an explorer who actively moves his arms, hands and fingers to get a tactual impression of his environment. Haptic perception builds upon information from two distinguished sensory systems. Cutaneous information stems from the contact of the skin with an object. Kinesthetic information includes information about movements and positions of the limbs and other body parts as well as about contractions of the muscles. In haptic perception, information from these systems is integrated. From here on, I will treat haptic perception as a single system.

In this thesis I limit myself to purely spatial properties. Here, it is useful to distinguish between haptic perception of space and haptic perception of form. When the exploring hand moves over a continuous surface it explores the form of that surface. When a number of discrete objects at distinct locations are compared, either by touching successively or by placing the two hands on different objects simultaneously, one compares their spatial relations and explores the surrounding space in general. The totality of spatial relationships might be called haptic space, or in other words, the haptically perceived space. Unfortunately, the quest for a formal geometrical description of haptic space has not proved successful yet and it might even be unviable. Different studies have shown that several distortions occur in haptic perception of space. However, attempts to describe these different distortions by some kind of non-veridical, but inherently consistent, haptic metric regularly failed. These distortions highlighted the fact that haptic spatial perception is not uniform over the explored space and it can therefore be termed as anisotropic. For instance, people regularly overestimate the length of radial movements (to and from the body) by about 10% over tangential ones (Cheng, 1968; Marchetti & Lederman, 1983; Revesz, 1934). Similarly, people overestimate the length of touched vertical lines as compared to horizontal ones (Casla et al., 1999; Heller et al., 1997). A third example of anisotropy in haptic space perception is the oblique effect. When people are asked to reproduce the orientation of an object, they do worse with oblique than with horizontal or vertical orientations (Gentaz & Hatwell, 1996, 1998; Lechelt et al., 1976; Luyat et al., 2001). Many further distortions already known from vision, like the tactual Müller-Lyer illusion, the Kundt illusion, the Poggendorff illusion and many others, have been reported by Revesz (1934). Altogether, the number of distortions and illusions in the haptic perception of space is large, and these often depend upon the way the haptic system derives the position and movement of the limbs, and the position and movement of objects with respect to the limbs.

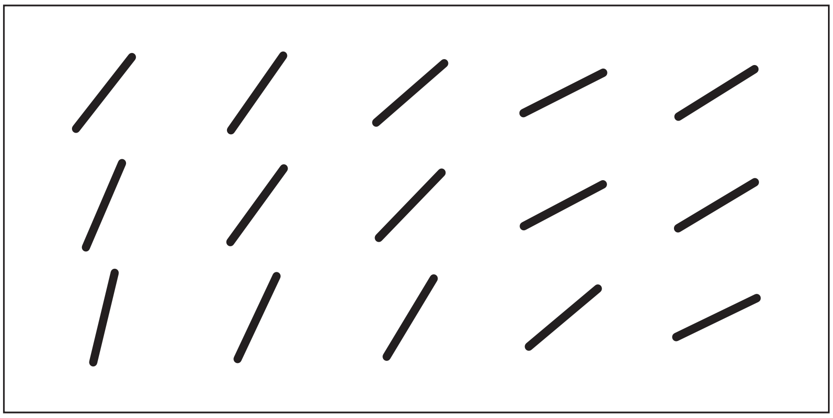

Figure 1. An example of perceptually parallel bars.

One of the most extensive lines of research that has shed some light on haptic perception of space focuses on a specific task, the parallelity task. In this task, blindfolded participants are instructed to rotate one or more bars parallel to another bar with a certain reference orientation (Kappers & Koenderink, 1999; Kappers, 1999). A repeatedly confirmed outcome is that people commit “errors” of as much as 90°. Here, “error” has to be understood in the correct sense: it denotes deviation from veridicality. These deviations are systematic, the scatter in repeated trials being at least an order of magnitude less. The typical pattern of deviations can be described as follows: deviations occur in a counterclockwise direction when the reference bar is on the right of the test bar, whereas they occur in a clockwise direction when the reference bar is on the left of the test bar (see Figure 1). This task was initially performed on the horizontal plane, but later studies confirmed identical patterns of deviations also on the midsagittal plane and on the frontoparallel plane (Kappers, 2002; Hermens et al., 2006). The origin of these deviations was thought to stem from biased spatial encoding processes. Spatial encoding can only occur with respect to one or more reference frames. When several reference frames are simultaneously available and actually employed, they may interfere with each other. The resulting encoding can thus be biased in the direction of one or more reference frames. In the next section I will turn my attention to the concept of reference frames and to the implementation of this concept in haptic spatial processing.

Reference Frames in Haptic Spatial Processing

It is trivial to say that the location of an object and its orientation are always referred to in one or multiple reference frames. We make implicit use of frames of reference whenever we define spatial relations. A reference frame gives the physical location relative to which an object's position and orientation are defined. This reference can be another object in space, but also a body part such as the eye or the hand, for instance. There is a general understanding that reference frames can be divided in two broad categories: egocentric and allocentric reference frames. In an egocentric reference frame, objects are represented with respect to the particular perspective of a perceiver, whereas an allocentric reference frame locates objects within a framework external to the perceiver and independent of his position. Several different body parts have been defined to be the origin of the egocentric reference frame. For instance, just to mention those probably involved in haptic perception: the hand (Carrozzo & Lacquaniti, 1994; Paillard, 1991), the arm (Flanders & Soechting, 1995; Soechting & Flanders, 1992, 1993), and the body (Luyat et al. 2001; Millar & Al-Attar, 2004). For convenience, a coordinate system, either in Cartesian or polar coordinates, is defined within a reference frame. For present purposes, however, the distinction between Cartesian and polar coordinates is not critical, as the formalisms are interchangeable.

As I mentioned earlier, the systematic deviations in the parallelity task were a strong indicator that the processes subserving our haptic representation of space are strongly linked to the reference frames in which the spatial information is encoded. It has been argued that the systematic deviations reflect the biasing influence of an egocentric reference frame (Kappers, 2003, 2004). This means that what is perceived as haptically parallel is between what would be parallel in an allocentric reference frame and what would be parallel in an egocentric reference frame. The origin of the egocentric reference frame has been suggested to be either the body midline (Kaas & van Mier, 2006; Kaas et al., 2007) or the hand (Kappers, 2004). In a body-centered reference frame two bars that are parallel within this frame would have the same orientation with respect to concentric circles centered on the body midline that are taken as reference lines. Likewise, in a hand-centered reference frame two bars that are parallel within this frame maintain the same orientation with respect to the hand. Evidence has supported a primary role of the hand-centered egocentric reference frame, although some influence of the body-centered reference frame could not be excluded (Kappers & Viergever, 2006).

Interestingly, the biasing influence of the egocentric reference frame has been shown to vary consistently between people. Some perform almost optimally, whereas others set the two bars almost perpendicularly to perceive them as parallel. These differences are believed to reflect the interaction between reference frames, where the contribution of the egocentric reference frame can be more or less heavily weighted. Different weighting of the contributions of reference frames seemed to depend also on the circumstances, such as the demands of the task or the available information. For instance, viewing the region of space directly above and around the haptic workspace improved performance by reducing the magnitude of the deviations (Newport et al., 2002; Zuidhoek et al., 2004). Non-informative vision thus enriched the available information about the external environment inducing a larger weight of the allocentric reference frame. In a similar line, the relative contributions of the allocentric and the egocentric reference frames changed following experimental manipulations of the temporal delay between the acquisition of the object's orientation and the succeeding parallel setting. Surprisingly, a 10-s delay had an ameliorating effect on performance (Zuidhoek et al., 2003). This improvement was again interpreted as reflecting a shift from an egocentric towards a more allocentric spatial representation over delay time, similar to findings of several visuomotor studies (Bridgeman et al., 1997; Carrozzo et al., 2002; Milner et al., 1999; Rossetti et al., 1996).

In sum, there are clear indications that all the above mentioned phenomena form part of a common mechanism based on several reference frames and their interdependencies. The idea of multiple reference frames and their mutual interactions is not confined to haptic spatial processing. A collection of studies, especially in visuomotor integration, has promoted the argument that most of the behavior of an active perceiver involves encoding of spatial information, and the transformation and combination of reference frames (Arbib, 1991; Battaglia-Mayer et al., 2003; Cohen & Andersen, 2002; Colby & Duhamel, 1996; Gross & Graziano, 1995).

Overview

The goal of this thesis is to gain insight into haptic perception of spatial relations. We investigated the human ability to haptically acquire and process spatial information with specific attention on the orientation of objects. Besides the accuracy of these processes, we were especially interested in identifying in which reference frames the objects are represented. Moreover, we approached the issue of how different reference frames are combined with each other and how this interaction can be influenced by introducing different task demands and by providing different information.

In *Chapter 2*, we describe the study on haptic spatial relations on the frontoparallel plane. The first goal of this study is to extensively explore the pattern of systematic deviations occurring in a bimanual parallelity task on the frontoparallel plane. Second, we try to relate the magnitude of the deviations to the way hands approach the objects. If the deviations and orientations of the hands correlate to a certain degree, it would suggest that spatial information is encoded in a hand-centered reference frame. In addition, the deviations could be interpreted as a consequence of a biasing influence of the egocentric reference frame on the allocentric reference frame.

In *Chapter 3*, we extend the body of literature on the haptic parallelity task to its three-dimensional version. The first question is whether the deviations participants make occur in a systematic manner also in the three-dimensional haptic parallelity task and if they are comparable with the deviations observed previously. Second, if the deviations have the same origin, they should be describable by a model that weights the impact of the involved reference frames. We discuss several models that, among other issues, try to discern the involvement of a hand-centered reference frame against a body-centered reference frame.

In *Chapter 4*, we examine the effects that additional information has on haptic spatial processing. We compare performance on the haptic parallelity task with performances in two experimental conditions. In the first case, additional visual information about the surrounding environment is provided. This information is thought to reinforce the strength of the allocentric reference frame and thus change the relative weighting between frames of reference. In the second case, interfering visual information is presented near the location of the haptic stimulus. The effect of visual interference might shed some light on the strength of the integration of visual and haptic information. Given the fact that usually participants largely differ in the magnitude of their deviations, it is of interest to relate these idiosyncrasies with the sizes of the effects of non-informative vision and visual interference.

In *Chapter 5*, we use a different paradigm to study haptic spatial processing, namely the bimanual haptic mental rotation task. In this task, participants have to judge the parity of two objects that may be differently oriented. These objects are positioned in different locations, and therefore the hands exploring them may also be differently oriented. Response times are measured for each judgment. Depending on the reference frame in which the orientation of objects is encoded we expect the response time function to shift accordingly. We interpret the results in a framework of multiple interacting reference frames, where the hand-centered reference frame has the major contribution.

In *Chapter 6*, we introduce the mental rotation paradigm in a visuo-haptic cross-modal context. Our interest is to explore how spatial information is encoded with respect to visual and haptic reference frames and how this information is then elaborated. We present participants with two objects: one can be haptically explored and the other visually, but both are positioned in the same spatial location. The task is to identify as quickly as possible the parity of the differently oriented objects. In the experiment we manipulate the orientation of the exploring hand with respect to the viewing direction. Moreover, we introduce a temporal delay between the haptic and visual explorations. We expect different response time patterns depending on how spatial information is encoded and compared across modalities, and these patterns help us identify which reference frames are relevant in cross-modal spatial processing. The findings can shed some light either on the existence of a common reference frame or on the interaction of multiple modality-specific reference frames.

Finally, the findings of *Chapters 2* to *6* are summarized and discussed in *Chapter 7*.

Chapter 2

Haptic Parallelity on the Frontoparallel Plane: The Involvement of Reference Frames

Abstract

It has been established that spatial representation based on the haptic modality is subject to systematic distortions. In this study, the haptic perception of parallelity on the frontoparallel plane was investigated in a bimanual matching paradigm. Eight reference orientations and 23 combinations of stimulus locations were used. The current hypothesis from studies conducted on the horizontal and midsagittal plane presupposes that what is haptically perceived as parallel is a product of weighted contributions from both egocentric and an allocentric reference frames. In our study, we assessed a correlation between deviations from veridical and hand/arm postures and found support for the role of an intermediate frame of reference in modulating haptic parallelity on the frontoparallel plane as well. Moreover, a subject-dependent biasing influence of the egocentric reference frame determines both the reversal of the oblique effect and a scaling effect in deviations as a function of bar positions.

Volcic, R., Kappers, A. M. L., & Koenderink, J. J. (2007). Haptic parallelity on the frontoparallel plane: The involvement of reference frames. *Perception & Psychophysics, 69*, 276-286.

Introduction

In order to interact effectively with the world, people must be able to reach for and manipulate objects in their immediate environment. These acts require the agent to deal with spatial relations of various objects with respect to the body. The space in which these relations are coded and in which the agent acts is a product of multiple perceptual modalities. When sensory input is limited to the single modality of touch, the perceptual space can be referred to as *haptically perceived space* or *haptic space*. The term *haptic perception* refers to tactual perception in which both the cutaneous sense and kinesthesis convey information about distal objects and events (Loomis & Lederman, 1986).

Although the idea appears counterintuitive, perceptual spaces (visual, auditory, or somatosensory) are typically structured differently from the corresponding physical spaces, and thus perceptual spatial judgments are generally non-veridical. Similarly, several earlier studies have established that the perception of haptic space, and consequently the perception of spatial relations, is far from veridical (Blumenfeld, 1937; Hermens et al., 2006; Kappers & Koenderink, 1999; Kappers, 1999, 2002, 2003, 2004, 2005; Newport et al., 2002; Zuidhoek et al., 2003). These studies were performed on the horizontal, midsagittal, and frontoparallel planes and involved numerous stimulus locations in unimanual or bimanual conditions, such as the parallelity, collinearity, mirroring, and pointing tasks. All of these tasks were performed on the horizontal plane, whereas only the parallelity task was performed on other planes. In the parallelity task, in which participants match the orientations of two bars, a common outcome has been repeatedly confirmed, that participants produce large systematic deviations from physical parallelity. In the parallelity task, systematic directional errors of more than 90° can occur. Moreover, the magnitude of these deviations is clearly subject-dependent.

Encoding the location and orientation of an object implies the existence of a frame of reference in which space coordinates can be defined. Classically, a distinction is made between allocentric and egocentric frames of reference (Berthoz, 1991; Klatzky, 1998); the latter can be fixed to the hand (Carrozzo & Lacquaniti, 1994; Paillard, 1991), the arm (Flanders & Soechting, 1995; Soechting & Flanders, 1992, 1993) or the body (Luyat et al., 2001; Millar & Al-Attar, 2004). Moreover, ample evidence supports the idea that specific attributes are defined in neither an allocentric nor an egocentric frame of reference, but in a frame that is intermediate to those two (Carrozzo & Lacquaniti, 1994; Flanders & Soechting, 1995; Luyat et al., 2001; Paillard, 1991; Soechting & Flanders, 1992, 1993). Accordingly, the experimental results obtained in the parallelity task can be described by applying the reference frame-based model devised by Kappers (2002, 2003, 2004, 2005). Specifically, an interaction between two reference frames, allocentric and egocentric, has been hypothesized, with the coordinate systems of the two frames having different origins. The origin of the allocentric reference frame can be considered to be independent of the actual position of the perceiver, since it is linked to the external space, is aligned with gravity, and defines spatial relations with respect to elements of the environment. It should be noted that the allocentric reference frame is defined as being anchored in the external space, even though initially it inevitably has to be defined via egocentric experiences. On the other hand, the origin of the egocentric reference frame is assumed to be coupled to the body or to a specific body part of the perceiver, like the arm or the hand. Therefore, changes in the perceiver's position relative to the allocentric reference frame lead to modifications of the egocentric reference frame. Accurate performance in the parallelity task could only be achieved if the haptic perception of parallelity relied on the allocentric reference frame, because the task itself is defined in allocentric terms. On the other hand, if haptic parallelity were based on the egocentric frame only, factors such as the rotation of the hand involved in a specific task, for example, would determine the amount of deviation from what is physically parallel. In practice, what feels haptically parallel is always intermediate between parallelity as defined by the allocentric frame and by the egocentric frame. In other words, haptic parallelity is determined by a biasing influence of the egocentric frame of reference. Hence, the experimental results can be interpreted as being weighted averages of the contributions of the two reference frames, and the magnitude of the deviations is determined by the degree to which the allocentric and egocentric reference frames combine with each other. Hermens et al. (2006) have proposed an alternative hypothesis suggesting that the deviations could be explained by errors in transferring the reference orientation from one hand to test bar position on the other hand. In contrast, several results, among them the correlations between deviations and hand orientations found by Kappers (2005), are not explainable by the transfer-of-information hypothesis and seem to disprove it.

In addition, a series of studies (Hermens et al., 2006; Kappers & Koenderink, 1999; Kappers, 1999, 2002, 2003, 2004) have explored the effect of the reference bar orientation on systematic deviations–that is, on errors in terms of the constant directional error (accuracy). The major observation has been that the biasing influence of the egocentric reference frame again plays a crucial role. Participants with smaller average deviations, who therefore relied more upon the allocentric representation, performed more poorly (i.e., had larger deviations) at oblique than at vertical and horizontal orientations, a phenomenon known as an *oblique effect*. Conversely, participants with larger average deviations showed a reverse oblique effect, performing better (i.e., having smaller deviations) at orientations that were oblique in an allocentric reference frame but were vertical or horizontal accordingly to their egocentric reference frame. Newport et al. (2002) reported another observation concerning the dependence on reference orientation in a slightly different experimental design. By studying only the effect of diverse oblique orientations, they found an almost linear increase in deviations as the sensing arm assumed more extreme postures.

Another branch of haptic perception studies (see below) has focused on the oblique effect by looking at the variability of the settings instead of at the accuracy. Variability and accuracy are independent measures, and variability has been observed to be greater at oblique orientations than at vertical and horizontal orientations. Many factors that could have some bearing on the oblique effect have been considered. For instance, some have suggested that the effect arises as a result of visual experience and imagery (Appelle & Countryman, 1986; Appelle & Gravetter, 1985). On the other hand, studies involving the use of different planes and different body and head tilts have suggested that gravitational cues play a certain role (Gentaz & Hatwell, 1996; Luyat, et al., 2001). Furthermore, the existence of the oblique effect has been ascertained both in children and blind adults (Gentaz & Hatwell, 1995, 1998; Gentaz & Streri, 2004). In particular, Gentaz and Hatwell (1998) showed the presence of the effect in both early- and late-blind people, refuting the hypothesis that visual experience plays a major role. In addition, the persistence of the effect has been observed in conditions that involved delayed reproductions and memory constraints (Gentaz & Hatwell, 1999; Lechelt & Verenka, 1980). Finally, the oblique effect has also been examined in intramodal and cross-modal conditions involving the haptic, visual, and somatovestibular system (Gentaz et al., & Raphel, 2001; Lechelt et al., 1976; Lechelt & Verenka, 1980). Whereas the latter studies have always examined only a few bar locations on a specific plane, the haptic space studies have concentrated on the systematic deviations that occur over the whole region of space within the reach of hands, defined as peripersonal or manipulatory space (Lederman et al., 1987).

The purpose of our study was to focus on the perception of haptic space on the frontoparallel plane. Blindfolded participants had to rotate a test bar in such a way that it felt parallel to a reference bar. Bars were displaced laterally with respect to the body midline and were easily reachable with the extended arms. The amount and direction away from physical parallelity and the orientation of the hand at different locations on the plane were measured. Since we hypothesize that hand/arm orientation is probably interconnected with the orientation of the egocentric reference frame, we expected the amount of deviation at a specific location to be at least partially correlated with the change in hand orientation. Recently, Hermens et al. (2006) conducted a study on the frontoparallel plane in which only a few bar locations were used, and consequently in which only a few hand/arm orientations were involved. This experimental limit has probably constrained the reference frame-based interpretation of the results of the parallelity task, because no correlation was found between hand orientation and deviation.

The primary aim of the present paper is to establish whether systematic deviations from what is physically parallel can be detected on the frontoparallel plane, and whether these deviations are comparable with those found in studies performed on the horizontal and midsagittal planes. Exploratory movements could be influenced by the plane in which the task is executed; therefore, it is of fundamental importance to compare performance on the three primary orthogonal planes. Only a thorough exploration of the patterns of deviations on different planes can lay the foundation for a comprehensive explanation of the distortions that occur in the haptic perception of space. Second, by monitoring numerous bar locations, we wanted to study the role that allocentric and egocentric reference frames play in determining the pattern of errors. Specifically, we wanted to find out whether it would be possible to describe our results by applying the reference frame-based model derived from earlier studies (Kappers, 2002, 2003, 2004, 2005). Our third aim, which was no less important, was to find out more about orientation dependency by taking into account a finely distributed set of possible matching orientations. The effect can be investigated over a considerable number of stimulus locations in our paradigm, making it possible to observe eventual modifications in the perception of orientation on the frontoparallel plane. Finally, since previous studies have shown that more egocentrically characterized participants display a reverse oblique effect, it will be significant whether the same kind of reversal occurs in the present research.

Materials and Methods

Participants

The eight undergraduates (seven male, one female) who took part in this experiment were remunerated for their efforts. None of them had any prior knowledge of the experimental design and the task. The handedness of the participants was assessed by means of a standard questionnaire (Coren, 1993), all were right-handed, except for one (participant E.W.) who was ambidextrous and one (participant L.W.) who was left-handed.

Apparatus and Stimuli

The set-up consisted of a large, vertically positioned whiteboard that could be adjusted in height. Protractors with a radius of 12 cm were printed on the whiteboard with their centers 30 cm apart, both horizontally and vertically. A subset of 10 protractors (indicated by filled circles in Figure 1) was used in this experiment. An aluminum bar, with an axle in the middle, could be inserted in the center of each protractor and rotated freely. Small magnets were attached under the bar to prevent accidental rotations. Two bars with a length of 20 cm and a diameter of 1 cm were used as the test and reference bar. The bars had an arrow-shaped end on one side that allowed the reference bar orientation and the test bar orientation to be read off with an accuracy of 0.5°.

Pictures of hand orientations were taken with a digital camera (Canon Digital Ixus 400). This camera produced jpeg files with a resolution of 2272 by 1704 pixels.

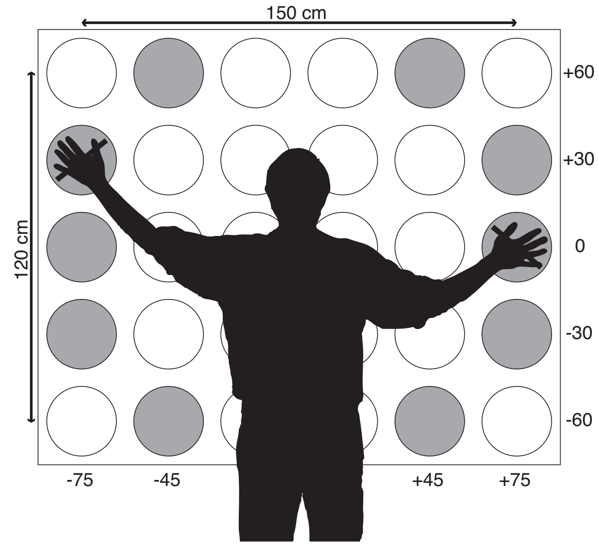

Figure 1. Schematic representation of a blindfolded participant performing the parallelity task on the frontoparallel set-up. The orientation of the bars represents a realistic final setting. The filled circles represent the locations at which the reference and bars could be fixed. The two bars were always positioned on opposite sides relative to the body midline.

Design

The reference bar was placed in a total of ten different locations. Five of the locations were distributed on the left side, and five symmetrically located positions on the right side of the board (filled circles in Figure 1). The test bar was always located on the contralateral side of the participant from the reference bar (i.e., on the right side when the reference bar was on the left, and vice versa). In total, there were 23 different combinations of locations of the two bars[1]. This specific set of stimuli was adopted in order to allow a sufficiently large number of location combinations in which participants could assume different hand/arm orientations without changing the posture of their elbow joints. As a comparison, in Hermens et al.'s (2006) study on the frontoparallel plane, bars were positioned at only four locations: (-45, 30), (-45, -60), (45, 30), and (45, -60). For each combination, the reference bar in our experiment was set at one of eight orientations, from 0° to 157.5° in steps of 22.5° (90° being the vertical orientation and 0° pointing horizontally to the body midline); the test bar was oriented randomly. The reference bar was located either on the left

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[1] The total number of possible combinations is 25, but the set-up used in this study did not allow including the two combinations of positions with the largest difference in height.

or on the right side of the body midline. The order of 368 trials in a block (23 combinations of bar locations × 8 orientations × 2 reference bar locations) was randomized for each participant. The block of 368 trials was repeated three times with different randomizations, for a total of 1104 trials per participant.

Procedure

Blindfolded participants had to perform a bimanual parallelity task. The participants were placed in front of the whiteboard at a distance of about 30 cm from the board, with the body midline aligned with respect to the midpoint of the set-up. The standing position was specified by a 30 × 30 × 2 cm platform attached to the floor. From this position, all locations on the whiteboard were within easy reach; therefore, no displacement of the body was either necessary or allowed. The height of the whiteboard was adjusted for each participant in such a way that the shoulders were at the same distance from the upper and lower bar locations (i.e., at height 0 in Figure 1).

The experimenter fixed the positions and orientations of the bars. Subsequently, the hands of the participants were placed on the bars, firstly on the reference bar and then on the test bar. Both bars were touched simultaneously for the whole duration of each trial; the left hand always touched the left bar, the right hand the right bar. The participants were instructed to rotate the test bar in such a way that they felt it to be parallel to the reference bar. No specific instruction was given about how to explore the two bars, and participants were allowed to use their fingers, palms and hands to touch the bars either statically or dynamically. They had 10 s to explore the bars and orient the test bar, which appeared to be a more than adequate amount of time. An electronic digital timer measured the time, with a beep signaling when it had run out. Participants then removed their hands from the set-up and the experimenter wrote down the measurement before starting with the next trial. No feedback was given on their performance. The experimental sessions ended after 1 h, in order to prevent fatigue for the participants, and were performed on separate days. Participants took on average 8–9 h to complete all of the sessions. They did not have the chance to see the set-up until all sessions were over, because it was covered both before and after each session.

After completion of the parallelity task, one more experimental session took place. In order to monitor the influence of hand orientation, the experimenter measured the orientations of both the left and right hands of each participant for each position employed in the parallelity task. We did this because the orientation of the hand indicates the orientation of the egocentric frame of reference fixed to the hand. In addition, the forearm and the hand were kept aligned throughout this experimental session. This method was previously utilized by Kappers (2005), who demonstrated a correlation between deviations and hand orientations. For this final session, participants resumed the standing position in front of the board, but with no bars attached to it. They were asked to place one hand on the board in a natural way (with no radial or ulnar deviation) at a position indicated by the experimenter. During this session, they were allowed to see the set-up in order to place their hand at the center of the protractor in the requested position. They were also asked to hold their extended fingers close to each other (finger adduction), as can be seen in Figure 2. The requested positions corresponded to the locations at which the bars had been situated during the parallelity task, and their order was randomized. When the participants' hand touched the board, a picture was taken with a digital camera. In total, three pictures were taken for each predetermined position. Hand orientation was defined as the pointing direction of the middle finger when the hand was lying on the surface of the board. Measurements of hand orientation were then extracted from all the pictures and averaged over the three repetitions. Participants took on average a half an hour to complete this session.

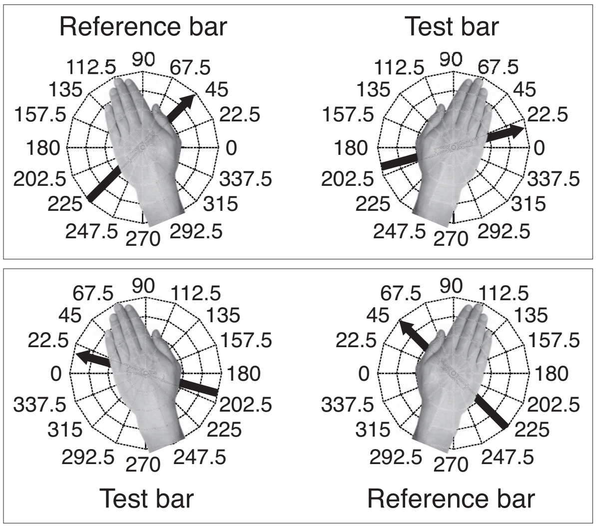

Figure 2. The orientation of the bar is defined by its location relative to the body midline. The 0° orientation of the reference bar always points horizontally to the projection on the board of the body midline. For the left-located reference bar, the degree of orientation increases in a counterclockwise direction, whereas for the right-located reference bar, it increases in a clockwise direction.

Data Analysis

The studies concerning haptic space perception have established that deviations vary in a systematic way. Deviations occur in a counterclockwise direction when the reference bar is on the right of the test bar, whereas they occur in a clockwise direction when the reference bar is on the left of the test bar. Such deviations are defined as the orientation of the left bar minus the orientation of the right bar; thus, the deviation specifies both the direction and the size of the error. It follows that positive values are assigned to deviations in the expected direction, and negative values to deviations in the opposite direction.

In the present study, the reference bar was located either on the left or on the right side of the body midline. In order to analyze the influence of the reference bar orientation, it was advantageous to combine data from the left and right reference bar conditions. To allow this data aggregation, reference orientations needed to be defined in such a way that the relation between the sensing hand and a specific orientation of the reference bar would be identical for both the left and right reference bar conditions. Figure 2 represents the method we used for codifying the data. The orientation of the reference bar was defined by its location relative to the body midline. When the reference bar was located on the left side of the body midline, the 0° reference orientation was set on the positive x-axis and the degree of orientation increased in a counterclockwise direction. In the opposite case, with the reference bar located on the right side of the body midline, the 0° reference orientation was set on the negative x-axis and the degree of orientation increased in a clockwise direction. By applying this relative orientation coding (body-midline-related orientations), we could be certain that left and right reference bar conditions were comparable in all respects. Specifically, in this way the relation between the orientation of the reference bar and the hand orientation became identical in all conditions, regardless of the location of the reference bar with respect to the body midline. The use of absolute orientations (i.e., having the 0° orientation set on the positive x-axis with angle increasing in a counterclockwise direction) with the whole data set would not permit this kind of aggregation. The difference between body-midline-related and absolute orientations will be addressed in more detail in the Results section.

The computation of the hand orientation difference was obtained by subtracting the orientation of the right hand from that of the left hand for each possible pair of reference and test bar positions. For instance, the hand orientation difference between the hands in the top box of Figure 2 would be calculated as the pointing direction of the left middle finger (112°) minus the pointing direction of the right middle finger (68°), and thus would result in a 44° hand orientation difference. Smaller hand orientation differences corresponded to the pairs of reference and test bar positions at the top of the board, whereas larger hand orientation differences corresponded to the pairs at the bottom part of the board.

In the repeated measures analysis on deviations, the assumption of sphericity was tested, and where necessary, the degrees of freedom were corrected using the Greenhouser-Geisser ε-correction. Our regression analyses on deviations met the assumptions of linearity, of homoscedasticity and of normally distributed residuals. Moreover, the multivariate regression analyses revealed that the assumption of no multicollinearity was also met. The minimal level of significance retained was .05.

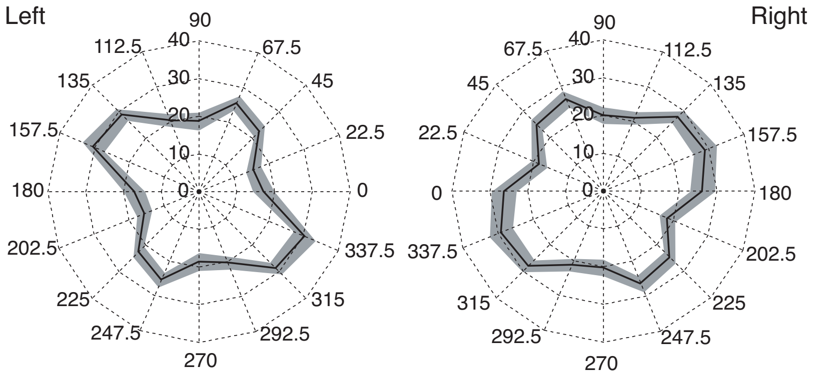

Figure 3. Polar plots of deviations, as a function of reference bar orientation for the left- and right-located reference bars, averaged over all participants and conditions. The gray areas represent the 95% confidence interval for the standard errors of the means.

Results

The polar plots in Figure 3 display the orientation-dependent deviations, averaged over all participants and all conditions; thus, each deviation is an average over 184 measurements. The data are presented separately according to the two reference bar locations (left side vs. right side). The distance from the center of each plot specifies the amount of deviation, and the eight axes define the reference bar orientations. The gray areas display the 95% confidence interval. The point symmetry was generated by mirroring the data from the measured 0°–157.5° range in the 180°–337.5° range. A pilot experiment supports the validity of this duplication of data, since both ranges yielded the same results. The patterns of deviations make it clear why the orientation of the reference bar has to be coded in relation to the body midline and not in absolute terms: When the reference bar was located on the right side, the performance at a specific orientation (e.g., 157.5° in Figure 3) could be compared with performance at the *body-midline-related* orientation of the reference bar on left side (i.e., 157.5° in Figure 3). As a consequence, the relation between the orientation of the reference bar and the hand orientation was identical in the two conditions. If *absolute* reference orientations had been used (i.e., 0° orientation on the positive *x*-axis for all data), the performances at identical orientations would correspond to different relations between the orientation of the reference bar and the hand orientation. This observation is corroborated by the following analyses, in which deviations were firstly analyzed with respect to the *absolute* reference orientation and second with respect to the *body-midline-related* reference orientation. The repeated measures analysis on deviations with reference bar location (left vs. right side of the board) and absolute reference bar orientation as factors revealed a significant interaction ($F(2.2,15.5) = 11.373, p < .001, \varepsilon = .316$), but no significant effect of bar location or orientation was found. In contrast, the repeated measures analysis on deviations with reference bar location (left vs. right) and body-midline-related reference bar orientation as factors revealed a significant effect of orientation ($F(1,7) = 6.963, p < .001$), but neither the bar location nor, more importantly, the interaction approached statistical significance. This means that since the body-midline-related orientations of the bars gave rise to equal scanning patterns, the performance at specific reference orientations in relation to the body midline had the same magnitude, regardless of the reference bar location. Consequently, all the data in the following representations and analyses were grouped over the two reference bar locations and expressed in terms of body-midline-related reference bar orientations. Therefore, the 0° orientation of the reference bar always pointed in the direction of the projection of the body midline on the frontoparallel plane, and the reference orientation angle increased in a counterclockwise direction for the left-positioned reference bar and in a clockwise direction for the right-positioned reference bar.

In Figure 4, deviations as a function of the reference bar orientation are shown for each of the eight participants. The polar plots are sorted in ascending order of average deviation. Each deviation is an average over 46 measurements, corresponding to the 23 different combinations of bar locations and the two reference bar locations. The most important aspect of Figure 4 is that the magnitude of the deviations is clearly subject dependent. Moreover, the direction of deviations is the same for all participants; that is, the positive sign of all deviations (except for 2 out of 64 data points) reveals a systematic pattern. If the test bar is located to the right of the reference bar, the errors made are always in a clockwise direction; likewise, if the test bar is located to the left of the reference bar, the errors made are always in a counterclockwise direction. It is also worth observing how reference bar orientation influenced the performance of different participants. Whereas participants with lower average deviations manifest clear superiority in both horizontal and vertical reference bar orientations, participants with higher average deviations exhibit less pronounced orientation dependence.

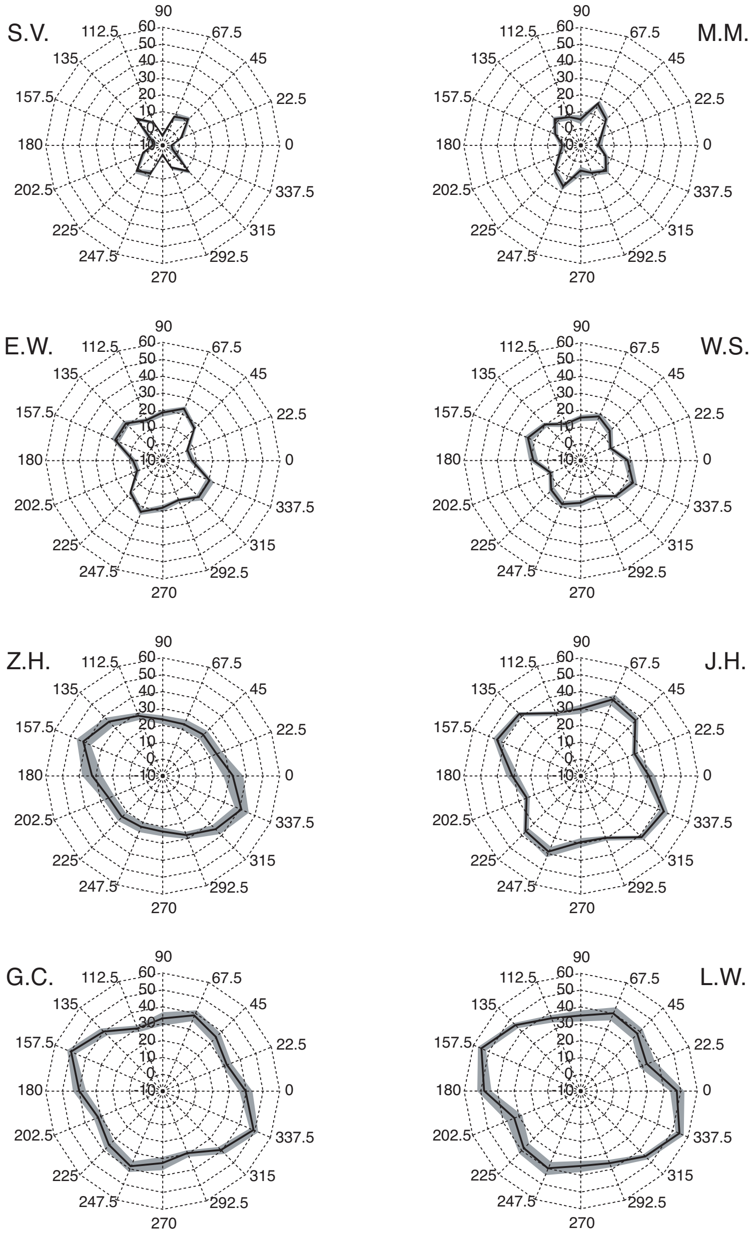

Figure 4. Polar plots of deviations as a function of reference bar orientation for the 8 participants, averaged over all conditions. The gray areas represent the 95% confidence interval for the standard errors of the means.

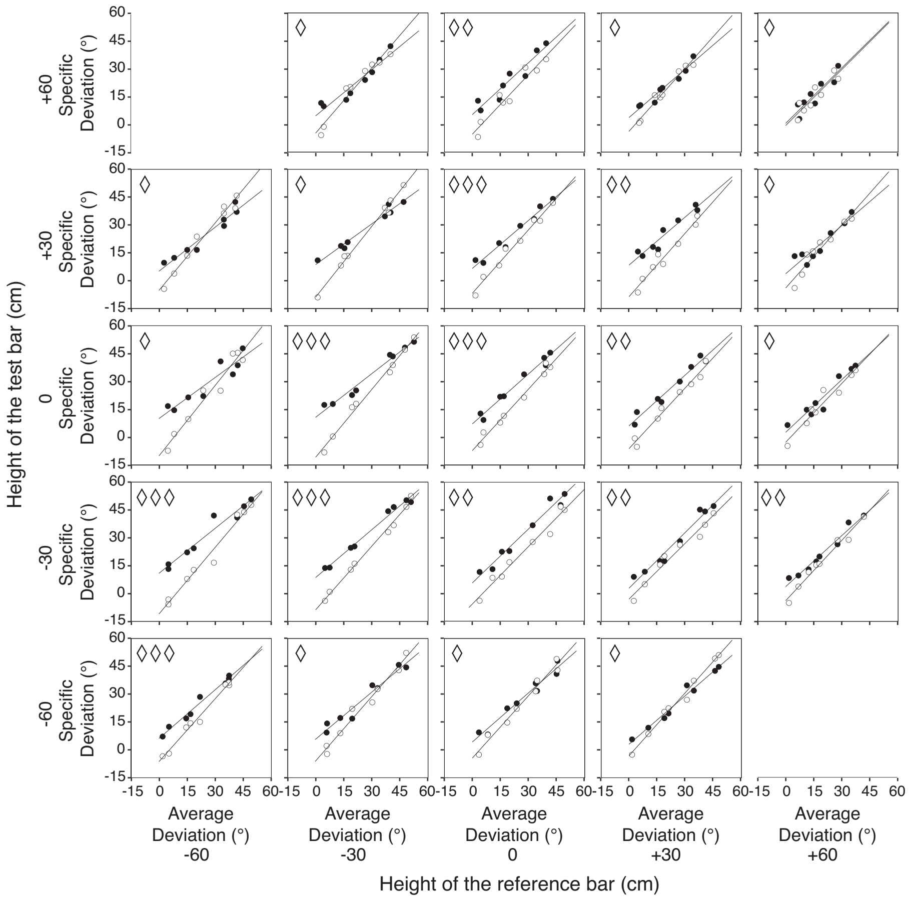

Figure 5. Scatter plots of specific deviations for the cardinal (0° and 90°) reference orientations (open circles) and the oblique (45° and 135°) reference orientations (filled circles), plotted against the average deviations. Each scatter plot displays the data of all participants for a different combination of bar locations, defined by the bar heights. Diamonds indicate the number of terms included in each best-fit regression model.

On observing the confidence intervals in Figure 4, one has the impression that they are scaled with the average deviations. A one-way ANOVA revealed that standard deviations differed significantly across participants ($F(7,56) = 7.893$, $p < .001$). In particular, polynomial contrasts revealed a significant positive linear trend in the data ($F(1,56) = 37.539$, $p < .001$). Furthermore, we regressed average deviations and average standard deviations, and found that the deviation was indeed a significant predictor of the standard deviation ($p < .001$). The standard deviation could be expressed as 5.66 + .14 * deviation ($r = .59$); that is, standard deviations widen slightly with increasing average deviations.

To obtain a clearer view of the oblique effect (larger deviations for oblique orientations) and of the reverse oblique effect (larger deviations for cardinal orientations), and to explore how orientations exert different influences on a participant's performance, we did a more detailed analysis. In the literature, all the studies on the oblique effect have considered only the two cardinal orientations (0° and 90°) and two oblique orientations (45° and 135°). Accordingly, in the following analysis, the aforementioned orientations were the only ones considered. Before pooling the data, we performed two-tailed paired *t*- tests separately for each participant to assess that the performance between the two cardinal orientations and between the two oblique orientations did not in fact differ. Figure 5 shows a matrix of scatter plots. In each scatter plot, specific deviations–that is, deviations at the cardinal (open circles) and oblique (filled circles) orientations–are plotted for each participant against that participant's average deviation. The average deviation of each participant was calculated separately for each graph. Each data point is an average over four measurements–specifically, over those obtained for the two reference bar locations and the two reference bar orientations. Data points are fitted with the least-squares method, which illustrates highly linear increases in all scatter plots.

The whole matrix in Figure 5 represents data for 23 different combinations of reference and test bar locations. The horizontal arrangement of a scatter plot in the matrix defines the location of the reference bar, whereas the vertical arrangement determines the location of the test bar. The location of a bar is described by one parameter–namely, the position of the bar specified by its height on the board (see Figure 1). This parameter comprises two possible bar locations, one on the left side and one on the right side of the board, as explained earlier. Since the second case is simply a mirror version of the first one, data were pooled.

In the majority of the scatter plots, participants with moderately lower average deviations reveal a clear oblique effect, so that cardinal orientations lead to lower average deviations than oblique ones. On the other hand, participants with higher average deviations exhibit less clear distinctions, in which cardinal deviations are sometimes equal to, or even larger than, oblique deviations. Statistical analyses of the difference between cardinal and oblique deviations were performed separately on the data from each scatter plot. The factors deviation (all cardinal and oblique deviations are included, but not averaged) and obliqueness (1 for cardinal, -1 for oblique deviations), as well as the interaction term deviation × obliqueness, were implemented in each multiple regression model. The multiple regression models with these three terms successfully explained the data from the scatter plots marked with the three diamonds in Figure 5. In these cases, the three-factors models accounted for the data significantly better than models with fewer factors, with the explained variance ranged from 96.4% to 99.1%. The significance of the interaction term points to a reversal of the oblique effect; that is, participants with higher average deviations tended to perform better with oblique orientations than with cardinal orientations. Regression models without the interaction term successfully accounted for data sets marked with two diamonds, and univariate regression models explained those data sets marked with one diamond. The explained variance ranged from 92.1% to 97.3% and from 82.2% to 96.5% for the two-predictor and one-predictor regression models, respectively. It is difficult to predict the reverse oblique effect for a specific combination of bar locations, because the prediction depends on both hand orientations as well as on both bar orientations. Moreover, the hand orientation of different participants for some particular locations could vary moderately (±15°). However, by focusing attention on the combinations of bar locations that were less prone to unpredictable results, we were actually able to observe the reverse oblique effect.

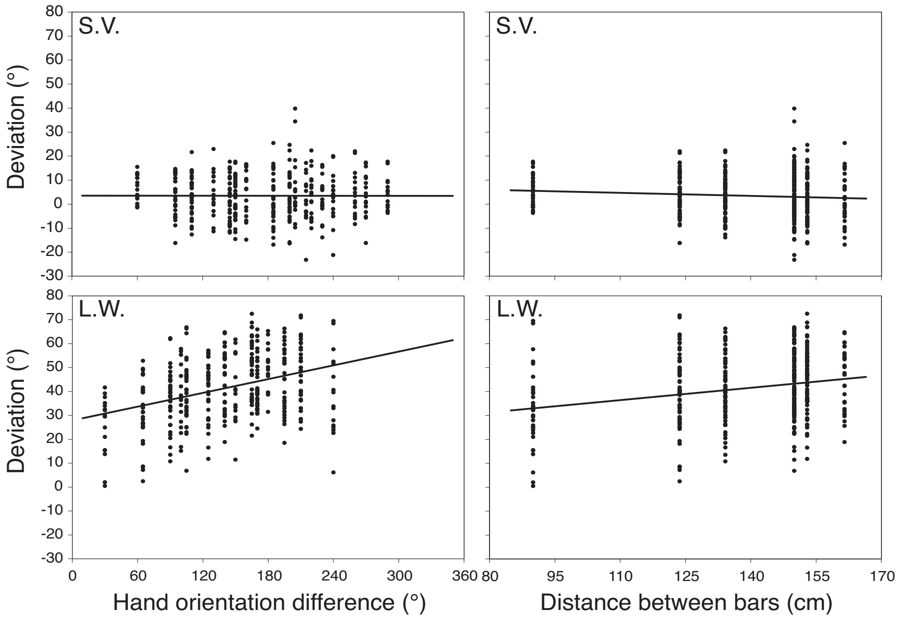

Figure 6. Scatter plots of deviations as a function of hand orientation difference (left panels) and distance between bars (right panels), for participant S.V. (top) and L.W. (bottom).

In the analysis of the complete set of data, it is important to consider the following two facts: namely, that the reference and test bars were located in various positions over the board and the two bars were separated by different distances. Participants' hands thus adopted heterogeneous orientations while reaching for the bars. Therefore, if the use of an intermediate reference frame can be assumed, a hand orientation dependency could be expected, especially in the group of participants with higher average deviations. In order to test this hypothesis, hand orientation differences for the bar location combinations had to be computed by subtracting the orientation of the right hand from that of the left hand. For instance, if the middle finger of the left hand was oriented at 170° and the middle finger of the right hand at 15°, the hand orientation difference would be 155°. A previous study (Kappers, 1999) showed that the magnitude of the deviations is mainly influenced by the horizontal distance between bars, and in a much smaller degree by the vertical distance. No influence of position relative to the body midline was observed. To determine the distance parameters, the relative distance between the locations of the two bars was calculated. The deviation dependencies on hand orientation difference and relative distance are shown in Figure 6. Specifically, the scatter plots in the upper row represent the data of the participant with the lowest average deviation (S.V.), and those in the lower row display the data of the participant with the highest average deviation (L.W.). It can be observed unequivocally that the deviations of S.V. do not depend on the two factors; on the other hand, the deviations of L.W. increase with both hand orientation difference and distance between the bars. The data for all the participants suggest that as the average deviation increases, the tendency to depend on both factors is progressively enhanced. Stepwise regression analysis for factor selection was conducted separately on the data of each participant. We decided on a significance level of .05 in order to determine which factors to include in the models, and on a level of .1 in order to determine which to remove. The stepwise procedure showed that neither hand orientation difference nor distance had an effect on the performance of the three participants with lower average deviations. However, with regard to the performance of the remaining participants with higher average deviations, the stepwise regression identified firstly hand orientation difference first ($p < .001$ for all participants) and then distance (between $p < .001$ and $p < .01$ for different participants) as significant predictors of deviation in all cases, except for J.H., who showed only a dependence on distance ($p < .001$).

Recently, Hermens et al. (2006) showed that deviations were larger when participants performed the parallelity task on the bottom part of the board. In the present study, it was moreover possible to examine how the reference orientation dependence combined with the effect of top versus bottom position. The data were clustered separately for each participant in two groups, according to the position of the bars on the board. When both the reference and test bar were positioned above shoulder height (the 30- and 60-cm heights in Figure 1), data were defined as belonging to the high group. Similarly, when both the reference and test bar were located below shoulder height (-30 and -60 cm in Figure 1), the data were assigned to the low group. All other combinations of reference and test bar positions were discarded from this analysis. Two-tailed paired *t*-tests on deviations were conducted separately for each participant to determine the difference in performance between the high and low groups. Deviations were significantly larger in the low group for four out of the five participants with larger average deviations. In contrast, participants characterized by smaller average deviations performed equivalently at both the top and bottom of the frontoparallel plane. The polar plots in Figure 7 represent the deviations as a function of the reference bar orientation for the high and low groups. The left polar plot shows the data of the participant with the smallest average deviation (S.V.), whereas the right plot shows the data of the participant with the largest average deviation (L.W.). S.V.'s deviations did not differ between the high and low groups, but on the contrary, L.W.'s deviations significantly increased (by 48.9%) when the bars were positioned on the bottom part of the frontoparallel plane. Moreover, it is worthwhile observing that for all participants, the relative differences in performances at different orientations were very similar, regardless of the scaling effect. Thus, the reference orientation influences performance in a consistent manner over the whole plane.

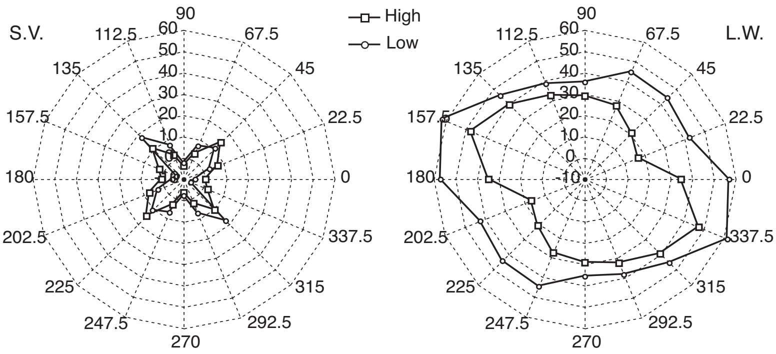

Figure 7. Polar plots of deviations as a function of reference bar orientation for participants S.V. (left) and L.W. (right). The two lines in each polar plot represent the data for combinations of bar locations corresponding to the top ("High") and bottom ("Low") parts of the frontoparallel plane.

Discussion

The comprehensiveness of the reference frame-based model in explaining the origin of large deviations in the parallelity task has now also been substantiated for the frontoparallel plane. This outcome, in combination with the previously obtained results on the other two primary orthogonal planes, strongly supports the role of the egocentric and allocentric frames of reference in modulating the haptic perception of parallelity.

Just as in the parallelity tasks executed on the horizontal and midsagittal planes (Kappers, 2002, 2003, 2004, 2005; Kappers & Koenderink, 1999), the magnitude of the deviations on the frontoparallel plane was found to be subject dependent. Despite the supposedly diverse exploratory movements that are performed on the three primary orthogonal planes, the average extent and the systematicity of deviations are fully comparable across planes. Previous studies indicated that participants who perform quite accurately probably rely more upon the allocentric reference frame. On the other hand, those who are less accurate, who can deviate by up to 90° from what is geometrically parallel, can be characterized as being more egocentric. In addition, our results suggest that as the participants' average deviations increase, their standard deviations also widen accordingly. Furthermore, performance as a function of reference orientation, averaged over all stimulus locations, shows the shape of a bimodal distribution that shifts slightly as participants' average deviations increase (see Figure 4). This observation suggests that the linear increase in deviations reported by Newport et al. (2002) was due to the limited set of reference orientations used in their study.

Kappers (2003, 2004) and Hermens et al. (2006) reported that the oblique effect reversed for participants with larger average deviations. When physically oblique orientations are approximately aligned with or perpendicular to the hand, they turn out to be cardinal with respect to the egocentric reference frame linked to the hand. The opposite holds true for the physically cardinal orientations. It should be noted that an oblique effect in the previously defined egocentric reference frame would appear as a reverse oblique effect in the allocentric reference frame. In general, the preeminence of the allocentric or egocentric reference frame for a particular participant thus determines whether the oblique effect will appear in a normal or reverse way. In the present study, although the multifarious assortment of combinations of hand and bar orientations could confuse the predictions, our findings were consistent with previous research: The reverse oblique effect tended to emerge for participants with larger deviations. The less pronounced manifestation of the reversal in our study was mainly due to the fact that the range of deviations in the present case was smaller than in the previous studies, which mentioned that the crossover point from normal to reverse oblique effect occurred at an average deviation of about 55°.

A more general overview of the orientation dependency of this effect can be provided by examining how the pattern of deviations at different reference orientations was influenced by diverse positions on the frontoparallel plane. Here again, performance could be distinguished on the basis of the participant's average deviation. Only the participants characterized by larger average deviations displayed a substantial increase in deviations when both the reference and test bars were located on the bottom half of the board (see Figure 7). This scaling effect in deviations could be due to the adoption of relatively unnatural hand postures or, more probably, to the larger hand orientation differences that characterized the locations at the bottom of the board. Furthermore, it is of interest to observe that the different reference orientations had a consistent influence over the whole of the frontoparallel plane. In other words, for our given set of reference orientations, the relative differences between the deviations remained stable, regardless of the locations of the reference and the test bars.

Strong support for our hypothesis of the involvement of intermediate frames of reference is supplied by the fact that the degree of the hand/arm rotation correlates with the amount of deviation (Kappers, 2005). This evidence has been observed on both the horizontal and midsagittal planes in a unimanual parallelity task. It should be possible to confirm this conclusion with a bimanual task, in which the orientation difference between the two hands would be considered instead of the hand rotation. However, Hermens et al. (2006) did not detect this relationship on the frontoparallel plane. Their failure to find an association between hand orientation differences and the settings was probably caused by the limited set of bar locations used in their study. In our research, however, we used a much larger sample of bar locations. Under these conditions, we were able to determine the existence of this relationship on the frontoparallel plane. We predicted that those participants who had higher average deviations would probably be more prone to rely on the egocentric reference frame and, thus, would display stronger correlations between hand/arm orientation differences and deviations. In fact, the deviations of this class of participants in our study did indeed correlate with their hand orientation differences. An even better correspondence was obtained when the relative distance between the bar locations was included in the model. On the other hand, participants with lower average deviations, who presumably based their space representation on the allocentric frame of reference, did not exhibit any dependence, either on hand orientation differences or on relative distance between the bars.

As the main result of this study, the hypothesis that an intermediate frame of reference modulates the haptic perception of parallelity has been verified on the frontoparallel plane. Thus, the magnitude of deviations is affected by the degree to which the egocentric or the allocentric reference frames dominates. This result nicely converges with previous findings on the horizontal and midsagittal planes and reinforces the suitability of the reference frame-based model. As a future step, it will be of extreme interest to combine the outcomes of these studies from all the primary two-dimensional orthogonal planes, in order to explore the haptic space perception of parallelity in three dimensions.

Chapter 3

Allocentric and Egocentric Reference Frames in the Processing of Three-Dimensional Haptic Space

Abstract

The main goal of our study is to gain insight into the reference frames involved in three-dimensional haptic spatial processing. Previous research has shown that two-dimensional haptic spatial processing is prone to large systematic deviations. A weighted average model that identifies the origin of the systematic error patterns in the biasing influence of an egocentric reference frame on the allocentric reference frame was proposed as an explanation of the results. The basis of the egocentric reference frame was linked either to the hand or to the body. In the present study participants had to construct a field of parallel bars that could be oriented in three dimensions. First, systematic error patterns were found also in this three-dimensional haptic parallelity task. Second, among the different models tested for their accuracy in explaining the error patterns, the Hand-centered weighted average model proved to most closely resemble the data. A participant-specific weighting factor determined the biasing influence of the hand-centered egocentric reference frame. A shift from the allocentric towards the egocentric frame of reference of approximately 20% was observed. These results support the hypothesis that haptic spatial processing is a product of the interplay of diverse, but synergistically operating frames of reference.

Volcic, R., & Kappers, A. M. L. (2008). Allocentric and egocentric reference frames in the processing of three-dimensional haptic space. *Experimental Brain Research*, *188*, 199-213.

Introduction

Our subjective experience generally supports the idea that our perception of space is veridical, since we efficiently move around our environment and interact with objects in it. In actual fact, although at first sight it may appear counterintuitive, the structure of a perceptual space (acquired via a single or a combination of modalities) is typically dissimilar from the corresponding physical space. As a consequence, perceptual spatial judgments are generally non-veridical. This dissimilarity between perceptual and physical spaces was noted long ago. For instance, von Uexküll (1909) coined the term *Umwelt* to describe the subjective world that a living being perceives and experiences. According to him, the environment that living beings perceive is not an objective and veridical representation of the physical world, but is instead a product of particular sensory modalities that each living being has. More specifically, von Kries (1923) presupposed the existence of separate visual and haptic spatial representations that inevitably differ from the physical structure of space.

The main interest of the present research was to focus our attention on haptic perceptual space and, particularly, on the ability in dealing with the spatial concept of parallelity. Interestingly, von Uexküll (1928) took for granted that haptic perception of space is veridical, although the opposite would be inferable from his previous work mentioned earlier. As an example, he supposed that the task of haptically matching the orientations of two spatially separated bars while blindfolded is manifestly a very simple operation. This supposition was contradicted by Hammerschmidt (1934) who actually performed the aforementioned experiment. None of the participants was able to orient a bar physically parallel to a second bar. This was the first study to show that perceptual haptic parallelity differs from physical parallelity (see Blumenfeld (1937) and von Skramlik (1937) for other studies with similar implications). This topic was later tackled by von Skramlik (1959) who confirmed the previous findings, albeit without proposing any theoretical explanation. Unfortunately, these studies merely observed and described the fact that what feels haptically parallel does not correspond to what is actually physically parallel.

Only recently have different studies started to focus on haptic perception of spatial relations with an emphasis on the perception of parallelity by directing their attention to the disentanglement of the underlying mechanisms. The haptic parallelity task was performed on the horizontal plane (Kappers, 1999; Kappers & Koenderink, 1999; Zuidhoek et al., 2003), and similarly on the midsagittal (Kappers, 2002) and on the frontoparallel planes (Hermens et al., 2006; Volcic et al., 2007). Large and, more importantly, systematic deviations from veridicality were found to consistently occur on all the three main orthogonal planes, thus, over the whole region of space directly in front of the participant (i.e., frontal peripersonal space). The magnitude of the deviations was shown to be participant-dependent with the deviations varying between 10° and 90° (Kappers, 2003).

The systematicity of the error patterns was the indicator that the processes subserving our haptic representation of space are tightly linked to the reference frames in which these internal representations are coded. Spatial knowledge may be stored in many ways and in many different formats, but it is quite straightforward that the spatial characteristics of an object have to be encoded with respect to some reference frame. Commonly, reference frames can be described in terms of two broad classes: egocentric reference frames, in which objects are represented relative to the perceiver, and allocentric reference frames, in which objects are represented relative to the environment that is extrinsic to the perceiver (for a review, see Soechting & Flanders, 1992). The view that the brain constructs multiple spatial representations is supported by several studies in different research fields showing that we are biologically equipped to have multiple reference frames at the same time (e.g., Arbib, 1991; Carrozzo et al., 2002; Colby & Duhamel, 1996; Farah et al., 1990; Gross & Graziano, 1995; Klatzky, 1998; Paillard, 1991). Besides, several different body parts have been defined to be the origin of the egocentric reference frame, for instance, just to mention those probably involved in haptic perception: the hand (Carrozzo & Lacquaniti, 1994; Paillard, 1991), the arm (Flanders & Soechting, 1995; Soechting & Flanders, 1992, 1993), and the body (Luyat et al., 2001; Millar & Al-Attar, 2004). A question that has been frequently raised is whether the different frames of reference operate independently or mutually influence each other. The preferential choice of one or the other reference frame could depend on the type of spatial problem to be solved. However, there is now abundant evidence that supports the hypothesis of synergistically operating spatial representations. The spatial characteristics of an object are thus coded neither in an allocentric reference frame nor in an egocentric one but in a frame that is intermediate to the two (Carrozzo & Lacquaniti, 1994; Cohen & Andersen, 2002; Flanders & Soechting, 1995; Luyat et al., 2001; Paillard, 1991; Soechting & Flanders, 1992, 1993). In fact, the concrete existence of an intermediate reference frame is questionable; the weighted average of the two reference frames would provide an equally effective but a more parsimonious solution, but this issue lies beyond the scope of this paper. Although more than just two frames of reference could interact with each other, a single egocentric reference frame was usually identified as the primary biasing source on the allocentric reference frame. A systematic error pattern would therefore indicate the biasing influence of that specific egocentric frame of reference.

On the basis of the existence of multiple reference frames and their interactions, it has been hypothesized that the systematic patterns of errors occurring in the haptic parallelity task are a product of a weighted average of an allocentric and an egocentric frame of reference (Kappers, 2004, 2005, 2007; Kappers & Viergever, 2006; Volcic et al., 2007). Specifically, the participant-dependent magnitude of the deviations is determined by the degree to which the egocentric and the allocentric reference frames combine with each other. This model proved to be robust in describing the deviations on all of the three main orthogonal planes. Furthermore, it was able to predict an unchanged deviating behavior in a task in which participants were asked to set the bars perpendicular to each other, and, a disappearance of the deviations in a task in which participants were asked to mirror in the midsagittal plane the orientation of the reference bar (Kappers, 2004). In the above mentioned studies, the hand, or more generically the forearm, was identified as the origin of the egocentric reference frame, although a contribution of an egocentric frame of reference linked to the body-midline could not be completely disregarded (Kaas & van Mier, 2006; Kappers, 2007). The indication that the hand-centered reference frame contributes most was shown by Kappers and Viergever (2006), who demonstrated a modulation of the magnitude of the deviations as a function of the relative orientations of the two hands. In other words, the deviations in perceived parallelity decreased when the hands were convergent, and increased when the hands were divergent. Since the bars were always in the same position relative to the participants' body, this modulation was certainly not caused by any reference frame fixed to the body, eyes or shoulders. Kappers (2007) has furthermore quantified the biasing influence of the hand-centered reference frame. The contribution of this egocentric reference frame was about 25% on average. In other words, the deviations correspond approximately to a quarter of a given mismatch between the allocentric and the hand-centered egocentric frames of reference.

The primary purpose of our study is to explore haptic space perception of parallelity in three dimensions. Blindfolded participants had to match the orientation of a whole field of bars in such a way that they felt as if they were parallel to a reference bar. Participants had the freedom to orient the bars in three dimensions, as opposed to the constraint of orienting the bars in only one plane, which was incorporated in all the previous studies. Several questions were addressed in this study. The key question was whether the deviations (if any) participants make occur in a systematic manner also in the three dimensional haptic parallelity task and if they are comparable in various aspects with the deviation patterns observed in the 2-D haptic parallelity task. If the processes underlying 3-D haptic perception of space also reflect the hypothesis of a weighted average model, then the systematic deviations should cluster along the direction of the mismatch between the involved reference frames. Therefore, what feels haptically parallel should lie in the plane defined by the allocentrically and the egocentrically parallel bars (see Figure 1). Moreover, participant-dependent differences in the magnitude of the deviations would be expected to reveal the different contributions of the two reference frames. If, ad absurdum, the egocentric reference frame would completely dominate, the perceived parallelity would equal the egocentrically defined parallelity. The biasing influence of a specific egocentric reference frame would be expressed in participant-specific, but approximately stable, weighting factors. The final question concerned the choice and the validation of a specific model that would accurately describe the patterns of deviations. The comparison of models will especially try to discern the importance of either the body- or the hand-centered reference frame. In this respect, a deeper inspection of the different models is given in the following section.

Models

A vast variety of alternative reference frame-based models can be considered as best predictors of the results. To this end, however, we shall give careful consideration to a limited set of the most likely candidates. The main distinctive criterion is encapsulated in the typology of reference frames that are considered in each class of models; they can be built on a single allocentric frame of reference or on a combination of an allocentric and an egocentric frame of reference. The implication is that the geometrical concept of parallelity in the different reference frames can lead to different physical outcomes. Accordingly, some caveats should be noted. In the allocentric reference frame that corresponds to physical Euclidean space two bars with the same physical orientation are defined as parallel. Thus, the parallelity is independent of the relative locations of these bars. On the other hand, in the egocentric reference frame fixed to the body, or to some body part, two bars that are parallel within this frame can change their orientation with respect to the environment as a function of a spatial transformation (such as a translation, a rotation, or both) of the body part to which this frame is fixed. As a consequence, two bars that are parallel in an egocentric frame of reference can actually have different physical orientations.

Veridical Model

The underlying idea that characterizes the veridical model is that only an allocentric frame of reference subserves our perceptual representation of the surrounding space. The origin of the allocentric reference frame is considered to be independent of the actual position of the perceiver since it is anchored to the external space and defines spatial relations with respect to elements of the environment. We assume that the allocentric reference frame is derived from an internal construct built from extracting the stable covariant features of the environment. Therefore, the allocentric reference frame has to be inevitably internalized through egocentric experiences. Since the allocentric representation reflects the physical features of the surrounding space, the extent of the errors, if any, should be space-invariant. On this basis, the *Veridical model* assumes that the settings are physically correct, that is, all the bars are parallel in the allocentric reference frame. Deviations are expected to be minimally scattered and independent from the spatial location.

Descriptive Models

These models serve the purpose of describing the general trend of the data by presupposing a systematic error pattern, but without any hypothesis about the origin of the error pattern. Two models are proposed, the second one being a more specialized version of the first model.

Systematic error model. This model presupposes that the deviations have a systematic directional error that is independent of the spatial location. The average deviation across participants is considered as the best predictor of the extent of the errors.

Participant-dependent systematic error model. This model surmises analogous deviations as the previous model, that is, a systematic directional error independent of the spatial location, with the addition that the extent of the error is considered to be participant-dependent. As a consequence, the average deviation of each participant is considered as the best predictor of the extent of the errors.

Weighted Average Models

The weighted average models presuppose that the perceptual representation of space is based on the existence of an allocentric and an egocentric frame of reference and their mutual interaction. According to this presupposition, what feels haptically parallel is intermediate between the parallelity defined by the allocentric frame of reference and the parallelity defined by the egocentric frame of reference. Thus, haptic parallelity is determined by a biasing influence of the egocentric frame of reference, and the deviations from veridicality vary systematically across the space. Formally stated, what feels haptically parallel (vector $\mathbf{x}_{Model}$) should lie in the plane spanned by the two vectors $\mathbf{x}_{Allo}$ (allocentrically parallel) and $\mathbf{x}_{Ego}$ (egocentrically parallel), as can be seen in Figure 1. Thus, the weighted average of the contributions of the allocentric and the egocentric frame of reference should determine the perceived parallelity:

$$\mathbf{x}_{Model} = (1 - w)\mathbf{x}_{Allo} + w\mathbf{x}_{Ego} \qquad (0 \leq w \leq 1). \tag{1}$$

The size of the weighting factor (w) modulates the relative contributions of the two reference frames. A higher weighting factor causes a greater impact of the egocentric frame of reference and, consequently, larger deviations that are biased in the direction of the egocentric frame of reference. The participant-dependent component in this class of models is expressed by the variable weighting factor.

Obviously, the fundamental issue is the selection of the anchor point of the egocentric frame of reference. In the literature mentioned earlier, focus was restricted to a body-centered egocentric reference frame and a hand-centered egocentric reference frame. Hence the weighted average models are grounded on the combination of either one of the two egocentric reference frames and the allocentric reference frame. On this basis, the following two models were considered:

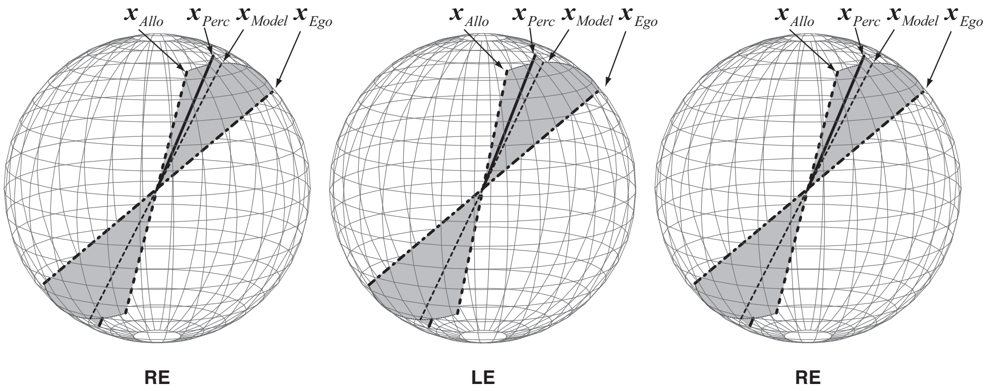

Figure 1. Stereoscopic representation of a generic weighted average model. A 3-D picture can be seen by cross-fusing the left two images or divergently fusing the right two images (RE – right eye, LE – left eye). The vector x_{Allo} represents an allocentrically defined parallel bar and the vector x_{Ego} represents an egocentrically defined parallel bar. According to the Weighted average model, what feels haptically parallel (x_{Model}) should lie in the plane spanned by these two vectors. The vector x_{Perc} represents a haptically parallel bar that differs slightly from the model prediction. Generally, the angle between x_{Perc} and x_{Model} defines the out-of-plane deviation and the angle between x_{Allo} and x_{Model} defines the in-plane deviation from veridicality.

Body-Centered Weighted Average Model

The body-midline is defined as the anchor point of the egocentric frame of reference ($\mathbf{x}_{EgoBody}$). Thus, two bars that are parallel within this egocentric frame would have the same orientation with respect to concentric circles centered on the body-midline that are taken as reference lines (see Figure 2a). Specifically, the orientation of the vector that would be defined as parallel to the reference orientation in this egocentric frame of reference is computed by taking into account the angle between the line connecting the reference bar to the body-midline and the line connecting the body-midline to a specific test bar. A change in the orientation of this vector would result in its rotation in the horizontal plane only. In this model, for each bar location two vectors ($\mathbf{x}_{Allo}$ and $\mathbf{x}_{EgoBody}$) define parallelity, one in the allocentric reference frame and one in the egocentric frame linked to the body-midline, respectively. The perceived parallelity would be determined by the weighting factor (w) calibrating the contributions of the two reference frames.

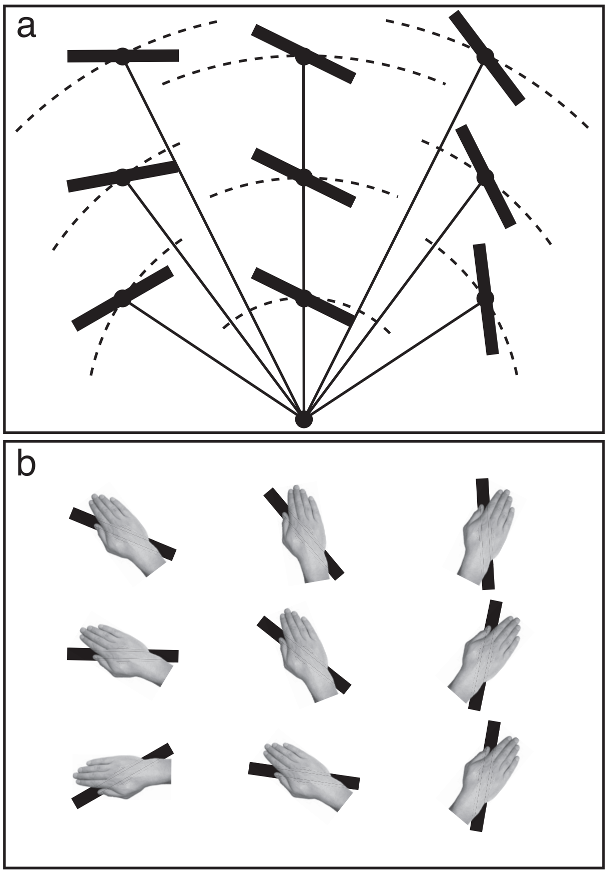

Figure 2. Representations of parallel bars in the Body- and Hand-centered reference frames (top view of the set-up). a Bars that are parallel in the Body-centered reference frame have the same orientation with respect to concentric circles centered on the body-midline. b Bars that are parallel in the Hand-centered reference frame have the same orientation with respect to the hand. Note that hand orientation can change both in slant and tilt. Changes in tilt are not depicted in this two dimensional figure.

Hand-Centered Weighted Average Model

The egocentric frame of reference ($\mathbf{x}_{EgoHand}$) is anchored to the hand. Therefore, two bars that are parallel within this frame of reference maintain the same orientation with respect to the hand, although their orientation with respect to the environment can change as a function of the hand displacement and its rotation (see Figure 2b). Any change in the orientation of the hand induces a change in the orientation of the hand-centered egocentric reference frame. The orientation of the vector that would be defined as parallel to the reference orientation in this egocentric frame of reference is computed by taking into account the change in the measured hand orientation (see Materials and methods) between each particular location of the test bar and the location of the reference bar. As a consequence, the orientation of this vector can vary both in the horizontal and in the vertical plane. As in the previous model, for each bar location two vectors ($\mathbf{x}_{Allo}$ and $\mathbf{x}_{EgoHand}$) define parallelity, one in the allocentric reference frame and one in the egocentric frame linked to the hand, respectively. The relative contribution of each reference frame is determined by the weighting factor (w).

Materials and Methods

Participants

Eight undergraduate students (six female and two male, 20–30 years of age) took part in this experiment and were remunerated for their effort. None of the participants had any prior knowledge of the experimental design and the task. The handedness of the participants was assessed by means of a standard questionnaire (Coren, 1993). All participants were right-handed.

Apparatus and stimuli

The set-up consisted of a table (150 × 75 × 75 cm) on which nine replaceable aluminum poles of variable height were fixed (for a schematic drawing see Figure 3). If the middle of one of the two longest table edges is defined as the origin with coordinates (0, 0), then the poles were placed at the x-coordinates -30, 0, and 30 cm, and at the y-coordinates 10, 30, and 50 cm, forming a rectangular grid of locations centered along the longest table edge. The poles were 12, 36, or 60 cm high (three poles for each height). On the top of each pole a rotatable aluminum bar with a length of 20 cm and a diameter of 1.8 cm was attached (see Figure 4). The rotation point of the bar was located in the middle of the bar's long axis. The bar could rotate in the vertical plane. Below each bar a half protractor was attached that allowed the bar orientation in the vertical plane to be read off with an accuracy of 0.5°. We define this orientation as tilt (θ). A 90° orientation corresponded to a horizontally oriented bar. By clockwise rotating the bar in the frontoparallel plane relative to the participant's viewpoint the orientation increases to its maximum at 170°. On the other hand, by counterclockwise rotating the bar in the frontoparallel plane the orientation decreases to its minimum at 10°. The poles could rotate along their vertical axis (360° range) and at the base of each pole a protractor was drawn that allowed the orientation in the horizontal plane to be read off with an accuracy of 0.5°. We define this orientation as slant (φ). A 0° orientation was parallel to the longest table edge with increasing angles in a counterclockwise direction. The 3-D orientation of the bar is defined by the tilt and the slant (elevation and azimuth are equivalent terms in use). For instance, a bar with a tilt of 90° and a slant of 90°, i.e. (90°, 90°), is horizontal, that is, parallel to the table plane, and perpendicular to the longest table edge. Bars were used both as test and reference bars; in the latter case a screw on the bar protractor and another screw on the pole protractor were tightened to prevent accidental rotations of the bar.

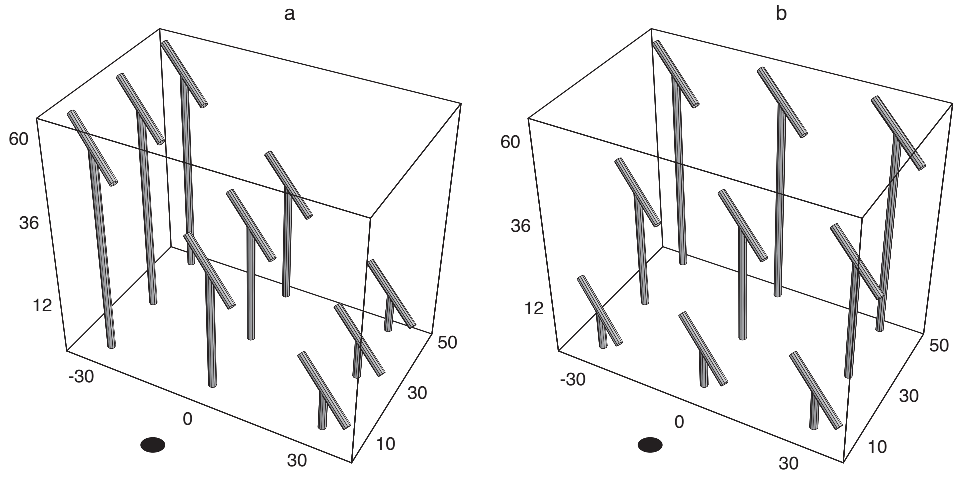

Figure 3. Representation of the spatial arrangement of the bars in the experiment. The reference bar was always positioned at the location (-30, 10). The black disks indicate the location of the participants' body-midline with respect to the set-up. a Left/right condition. b Far/near condition.

Design

The nine bars were arranged in two particular dispositions corresponding to different plane orientations and inclinations (see Figure 3). In the Left/right condition the bars with the 60 cm height were located at x = -30 cm, those with the 36 cm height at x = 0 cm, and those with the 12 cm height at x = 30 cm (see Figure 3a). In the Far/near condition the bars with the 12 cm height were located at y = 10 cm, those with the 36 cm height at y = 30 cm, and those with the 60 cm height at y = 50 cm (see Figure 3b). In the first condition the rotation points of the nine bars define a plane that is inclined from left to right, whereas in the second condition the rotation points form a plane that is inclined from far to near. The Far/near plane had a larger inclination than the Left/right plane since the distances between the y-coordinates of the poles are shorter than the distances between the x-coordinates. In both conditions the reference bar was positioned at the location (-30, 10), thus on the left side near the longest table edge. At all the other locations test bars were positioned. For each condition the reference bar was set at different orientations that can be divided into two categories, namely reference bar orientations that were lying in the planes defined by the rotation points of the bars (In-plane reference bars), and reference bar orientations that were at a certain angle with these planes (Out-of-plane reference bars). No Out-of-plane reference bar was normal to the plane. For the Left/right condition the orientations (120°, 45°) and (60°, 135°) were given to the In-plane reference bars, whereas the orientations (30°, 45°) and (150°, 135°) were given to the Out-of-plane reference bars. Similarly, for the Far/near condition the orientations (50°, 45°) and (50°, 135°) were given to the In-plane reference bars, and the orientations (140°, 45°) and (140°, 135°) were given to the Out-of-plane reference bars. The order of eight trials (2 planes × 2 reference bars relations with the plane × 2 reference bar orientations) was randomized for each participant. The block of eight trials was repeated three times with different randomizations, which amounted to 24 trials per participant and a total of 192 measurements per participant.

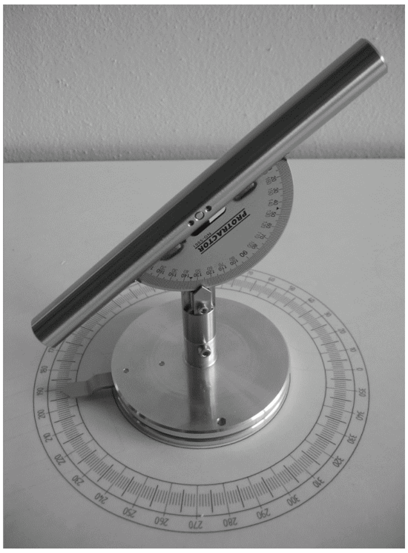

Figure 4. A close-up of the bar used in the experiment with the half protractor on the bottom of the bar indicating the tilt (θ) and with the protractor at the base of the pole indicating the slant (φ).

Procedure

Blindfolded participants had to perform the 3-D parallelity task unimanually. Participants were placed in front of the longest edge of the set-up. The floor in front of the set-up was marked specifying the locations on which the two participants' feet had to be positioned. Their body midline was aligned with respect to the mid-point of the set-up and was approximately 25 cm from the table edge (see the black disks in Figure 3). From this position all the bars on the top of the poles were within easy reach; therefore, no displacement of the body or bending of the upper body was either necessary or allowed.

Before the start of the experiment and before each trial the experimenter guided the right hand of blindfolded participants over the nine positions that defined the set of bars of the succeeding trial. In addition, the participants were encouraged to voluntarily explore the set of positions to acquire confidence in locating the bars without the help of vision. It should be noted that during this phase all nine bars were randomly oriented. Subsequently, the experimenter fixed the orientation of the reference bar and the right hand of the participants was placed on that bar. The participants were instructed to rotate all eight test bars in such a way that they felt all the bars were parallel to the reference bar. They could choose the order and, if needed, they could repeatedly switch between the same pair of bars. Importantly, it was never the case that two bars could be touched at the same time with their hand. Participants were allowed to use their fingers, palms and hands to touch the bars either statically or dynamically. However, one constraint was imposed on their exploratory behavior: they were permitted to approach the bars only from above. This limitation prevented them from exploring the bars from the side and simultaneously touching the poles on which the bars were attached, thereby giving them extra cues about their orientation. Neither during the trials nor between trials could the participants touch the table. To explore the bars and orient them they had five minutes, which appeared to be a more than adequate amount of time. An electronic digital timer signaled time when two minutes and one minute of the trial were left and when the time had run out. Participants removed their hand from the set-up and the experimenter wrote down the orientations before starting with the next trial. No feedback was given on their performance. The experimental sessions ended after one hour to prevent fatigue of the participants and were performed on separate days. They took on average 4 h to complete all sessions. Participants did not have the chance to see the set-up until all sessions were over, because it was covered before and after each session.

After the completion of the 3-D parallelity task one more experimental session was performed. In order to examine the influence of hand orientation, the orientation of the right hand was measured for each bar position employed in the 3-D parallelity task. This method enabled the orientation of the egocentric reference frame fixed to the hand to be calculated for each bar position. In previous studies on the haptic parallelity task conducted on the main orthogonal planes it was proven to be a valid method in demonstrating a correlation between deviations and hand orientations (Kappers, 2005, 2007; Volcic et al., 2007). Participants resumed their position in front of the set-up, this time without wearing the blindfold. The bars were distributed at the same locations as either in the Left/right condition or in the Far/near condition. They had to lay their right hand sequentially in a natural way (no radial or ulnar deviation) on the top of each of the bars including the reference bar that was then rotatable. Moreover, they were asked to hold their extended fingers close to each other (finger adduction). The participants' task was to align the bar to the middle finger, thus to the hand's major axis. The natural way of laying their hand on the bar closely corresponded to the orientation of the hand at the same location during the execution of the first experimental session. Several finger movements were certainly present in the first experimental session, but more importantly the orientation of the hands' major axis was quite stable. We assume that this hand orientation corresponds to the orientation of the egocentric reference frame at each bar location. The orientation of the hand was specified by the tilt and slant angles of the bar. The tilt angle refers to the up–down orientation of the hand, and the slant angle refers to the left–right orientation. The participants did not rotate the hand around its major axis during the 3-D parallelity task, because they had always to approach the bars from above. For this reason we limited the definition of the hand's orientation only to the tilt and the slant angle of the bar that the participants aligned to their hand. The hand orientations of each participant were measured for both the Left/right condition and the Far/near condition and repeated three times. Participants took on average twenty minutes to complete this session.

To estimate the variability of the hand orientation measurements we calculated the standard deviations for each bar location over the three repetitions. Standard deviations were rather small (on average 2°) and they did not vary for the different bar locations suggesting that the hand orientation measurements gave a good estimate of the orientation of the hand-centered egocentric reference frame.

Data Analysis

The orientations of the bars are specified by the tilt (θ) and slant (φ) angles. Since the bars were all of equal length, we will treat them as unit vectors in $\mathbb{R}^3$ with the origin (0, 0, 0) coinciding with the rotation point of each bar. The angular difference between two vector orientations can be expressed as a one-parameter angle, that is, the absolute angular difference between the vectors, or by several two-parameter angles. Our focus will be directed to three alternative methods for calculating the deviations from veridical. All three methods are based on two-parameter errors and they are interconnected with the different models employed in this study.

In the first method (Allo method) the errors are computed relative to the allocentric frame of reference. The *slant deviation* corresponds to the angular difference between the slant (φ) angle of the reference bar and the slant angle of the test bar. A positive sign is assigned to the deviations in the clockwise direction, whereas a negative sign is assigned to the deviations in the counterclockwise direction. The *tilt deviation* corresponds to the angular difference between the tilt (θ) angle of the reference bar and the tilt angle of the test bar. A positive sign is assigned to the deviations in the direction of the upward normal of the horizontal plane, and, conversely, a negative sign is assigned to the deviations in the opposite direction.

In the second method (Body method) the errors are computed in the context of the Body-centered weighted average model. Let $\mathbf{x}_{Perc}$ be a vector that corresponds to the orientation of a bar set by a participant, thus to the orientation that feels haptically parallel to the reference bar (see Figure 1). If the haptic perception of parallelity were veridical the vector $\mathbf{x}_{Perc}$ would be aligned with $\mathbf{x}_{Allo}$. Otherwise, the vector $\mathbf{x}_{Perc}$ would point to some other direction. In this case, the deviation of the vector is defined with regard to the plane spanned by the vectors $\mathbf{x}_{Allo}$ and $\mathbf{x}_{EgoBody}$. The vector $\mathbf{x}_{EgoBody}$ coincides with the parallelity defined in the egocentric frame of reference linked to the body-midline. The *in-plane$_{Body}$ deviation* is defined as the angle between $\mathbf{x}_{Allo}$ and the projection of $\mathbf{x}_{Perc}$ on the plane. A positive sign is assigned to the deviations in the direction of $\mathbf{x}_{EgoBody}$, whereas a negative sign is assigned to the deviations in the opposite direction. Similarly, the *out-of-plane$_{Body}$ deviation* is defined as the angle between the vector $\mathbf{x}_{Perc}$ and its projection on the plane. The sign of the out-of-plane$_{Body}$ deviation is defined with respect to the normal of the plane calculated as $\mathbf{x}_{EgoBody} \times \mathbf{x}_{Allo}$. A positive sign is assigned to the deviations in the direction of the normal, and, conversely, a negative sign is assigned to the deviations in the opposite direction.

In the third method (Hand method) the errors are computed in the framework of the Hand-centered weighted average model. The reasoning regarding the computations of these errors is identical to the second method, with the only distinction being that the deviation of the vector is defined with regard to a different plane, namely the plane spanned by the vectors $\mathbf{x}_{Allo}$ and $\mathbf{x}_{EgoHand}$. In this case the vector $\mathbf{x}_{EgoHand}$ coincides with the parallelity defined in the egocentric frame of reference linked to the hand. As it was shown in the description of the previous method, the *in-plane$_{Hand}$ deviation* is defined as the angle between $\mathbf{x}_{Allo}$ and the projection of $\mathbf{x}_{Perc}$ on the plane. A positive sign is assigned to the deviations in the direction of $\mathbf{x}_{EgoHand}$, whereas a negative sign is assigned to the deviations in the opposite direction. Likewise, the *out-of-plane$_{Hand}$ deviation* is defined as the angle between the vector $\mathbf{x}_{Perc}$ and its projection on the plane. The sign of the out-of-plane$_{Hand}$ deviation is defined with respect to the normal of the plane calculated as $\mathbf{x}_{EgoHand} \times \mathbf{x}_{Allo}$. A positive sign is assigned to the deviations in the direction of the normal, and, conversely, a negative sign is assigned to the deviations in the opposite direction. It has to be noted that according to the weighted average models when $\mathbf{x}_{Allo}$ and $\mathbf{x}_{Ego}$ coincide the plane spanned by these vectors is not defined. Therefore, it is not possible to define the *out-of-plane* and *in-plane deviations*. However, this special case did not occur in our study.

The planes with respect to which we calculated the deviations (both Body and Hand) were computed as a function of the reference bar orientation and the position of the bar with respect to either the body-midline or the orientation of the hand (see equation 1). The planes in the Hand method were computed separately for each participant, since the hand orientations could vary between them.

To estimate the contributions of the allocentric and the egocentric frame of reference in the two weighted average models the least-square method was applied. The weighting factor (w) was computed by minimizing:

$$\sum \alpha_i^2(w), \tag{2}$$

with respect to w. α_i is the angle between the measured orientation $\mathbf{x}_{Perc}$ and $\mathbf{x}_{Model}(w)$ for a single bar. The index i refers to the eight measured orientations obtained in a single trial. Separate minimization procedures were performed for the Body-centered and Hand-centered weighted average models. Therefore, a total of 24 weighting factors per participant were computed for each egocentric reference frame (linked to the hand or to the body-midline). This measure specifies the biasing influence of the egocentric reference frame.

The different models were compared by means of two methods: first, an approximate estimate of the accuracy of each model was given by comparing the observed settings with the predictions of the models; second, the best-fitting model was selected on the basis of Akaike's information criterion, which evaluates the complexity of a model against its accuracy in fitting the data (for details, see Appendix).

Results

Our results showed that participants systematically misoriented the test bars with respect to veridicality, that is, with respect to a field of physically parallel bars. For all participants, a bar on the right side of the set-up has to be rotated clockwise in the horizontal plane to be perceived as parallel to a bar on the left side, and, simultaneously, a bar located lower has to be rotated clockwise in the sagittal plane (seen from the right side) to be perceived as parallel to a bar located higher. To explore the systematicity of the errors participants made the data were analyzed by converting them into the two-parameter angles according to the three methods explained in the Data analysis section.

Comparison of the Analyzing Methods

The bar charts in Figure 5 represent the mean slant, in-plane$_{Body}$, in-plane$_{Hand}$ deviations, and the mean tilt, out-of-plane$_{Body}$, out-of-plane$_{Hand}$ deviations, expressed both as signed and unsigned errors for each participant. The error bars indicate the standard errors of the mean. It should be noted that the signed deviations define the magnitude and the directionality of the errors, whereas the unsigned deviations combine the magnitude of the errors with the variable error component. By considering all the signed deviations, represented in the first row of Figure 5, it is evident that the slant and in-plane deviations (Body, Hand) consistently point in the same direction, although the extent of the error is participant-dependent. On the other hand, all the signed tilt and out-of-plane deviations (Body, Hand) are scattered around zero. Simple *t*-tests conducted separately on the data of different participants and separately for the three analyzing methods were run to check if, on the one hand, the signed slant and in-plane deviations, and, on the other hand, the tilt and out-of-plane deviations differ from zero. For all participants, as is already clear from Figure 5, the signed slant and in-plane deviations were significantly different from zero (Allo: $7.09 \le t(191) \le 14.24$, $p < .001$; Body: $8.01 \le t(191) \le 14.79$, $p < .001$; Hand: $13.65 \le t(191) \le 18.54$, $p < .001$). On the contrary, the differences between the signed tilt and out-of-plane deviations and zero proved to be mostly not significant. Specifically, for both Allo and Body analyzing methods, the out-of-plane deviations resulted to be significantly different from zero for participants MT (Allo: $t(191) = 2.4$, $p < .05$; Body: $t(191) = 2.27$, $p < .05$) and RW (Allo: $t(191) = 3.43$, $p < .001$; Body: $t(191) = 2.93$, $p < .005$). Only for the Hand analyzing method were the signed out-of-plane deviations not significantly different from zero for all participants.

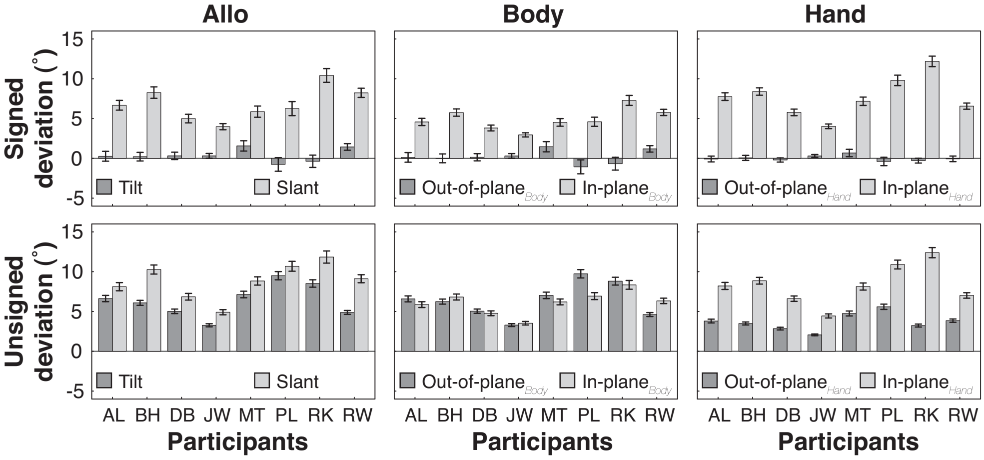

Figure 5. Bar charts that represent the deviations from veridicality for each participant according to the three analyzing methods. The mean slant and tilt deviations are presented in the left panels, the in-plane$_{Body}$ and out-of-plane$_{Body}$ deviations in the middle panels, and the in-plane$_{Hand}$ and the out-of-plane$_{Hand}$ deviations in the right panels. The error bars indicate the standard errors of the mean ($N = 192$). Signed deviations are shown in the top panels and unsigned deviations are shown in the bottom panels.

In the second row of Figure 5 the unsigned deviations are plotted. Since all the slant and in-plane deviations are strongly biased in one direction, the difference between the signed and the unsigned slant and in-plane deviations is almost unnoticeable, which means that only a few settings were actually in the opposite direction. This strong similarity between the signed and the unsigned slant and in-plane deviation underlines the strength of this bias. On the other hand, the unsigned tilt and out-of-plane deviations provide additional information about the magnitude of these deviations. If these deviations are compared among the three analyzing methods, it is clear that the unsigned out-of-plane$_{Hand}$ deviations are the smallest. This evidence is supported by paired *t*-tests conducted separately on the data of different participants in which the three analyzing methods were compared. The unsigned out-of-plane$_{Hand}$ deviations were for all participants significantly smaller than both the unsigned tilt and out-of-plane$_{Body}$ deviations (Allo vs. Hand: $4.23 \leq t(191) \leq 10.94$, $p < .001$; Body vs. Hand: $3.42 \leq t(191) \leq 11.19$, $p < .001$). The comparison of the unsigned tilt and out-of-plane$_{Body}$ deviations did not lead to any significant result. The minimal level of significance in these analyses was lowered to .017 (Bonferroni correction) because of multiple comparisons. In an overall view of the unsigned deviations it is also noteworthy to put alongside the two orthogonal error measures and consider their relative magnitudes. A series of paired *t*-tests showed that the unsigned slant deviations were significantly larger than the unsigned tilt deviations with an average difference of 2.4° ($t(7) = 5.49$, $p < .001$). Similarly, the unsigned in-plane$_{Hand}$ deviations were significantly larger than the unsigned out-of-plane$_{Hand}$ deviations with an average difference of 4.6° ($t(7) = 6.19$, $p < .001$). On the contrary, the difference between unsigned in-plane$_{Body}$ deviations and unsigned out-of-plane$_{Body}$ deviations was found to be not significant.

Comparison of the Models

One of the main purposes of the analysis was to select the model that best suits the gathered data. In this respect, first, the data were compared with the predictions of the models, and, second, Akaike's information criterion was applied to select the best-fitting model. The predictions of the weighted average models were based on the positions of the bars with respect to the body-midline or on the measured hand orientations. The weighting parameter was determined for each participant individually by averaging the weighting factors computed as explained in the Data analysis section.

In Figure 6 the mean absolute deviations between the data and each model with the relative standard errors of the mean are shown, individually for each participant. The absolute deviation is a one-parameter error measure expressing the angular difference between a setting and the prediction of a model for that particular setting. From Figure 6 it is evident that the Hand-centered weighted average model provides the smallest discrepancy with the data and it does so consistently for all participants. Moreover, the scatter of these deviations is rather low in contrast to that observed for the other models. The absolute deviations were constant for the different bar locations indicating no systematic error in the predictions of the model. The opposite was true for the other models that showed systematic absolute deviations as a function of the bar location. The Hand-centered weighted average model was thus able to better capture the participants' behavior over the whole set of bars.

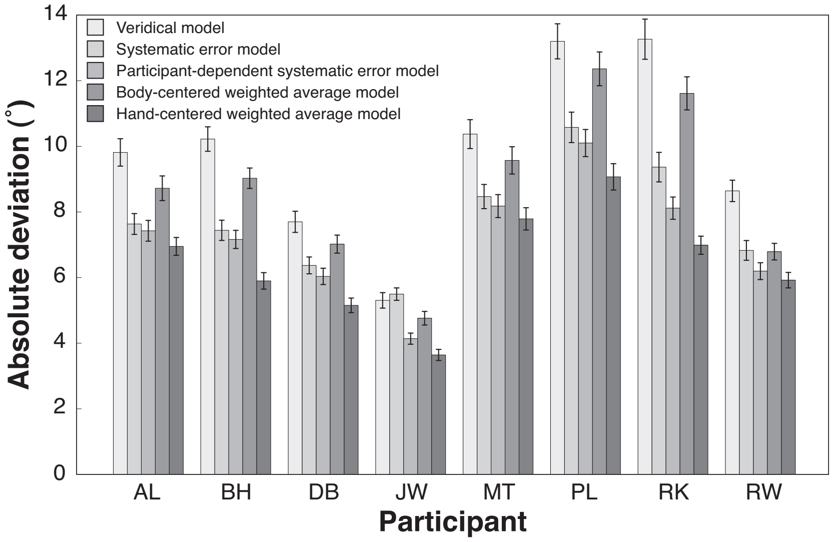

Figure 6. Mean absolute deviations between the data and the five models for each participant. The absolute deviations of the Body- and Hand-centered weighted average models are computed using the average weight specific for each model and participant. The error bars indicate the standard errors of the mean (*N* = 192).

The appropriateness of the set of models was evaluated using Akaike's information criterion (see Appendix). The relative probability of each model being correct among the set of candidate models was assessed by considering, on one side, the sum-of-squares of the errors between each model prediction and the set of data, and, on the other side, the different number of parameters that each model necessitates. The Veridical model and the Descriptive models do not have any free parameter, because they predict the same outcome for all bar locations. On the other hand, both the Body- and the Hand-centered weighted average models have one free parameter, namely the weighting factor (w) calibrating the contributions of the allocentric and the egocentric reference frames[1]. This procedure was executed separately for each participant and Akaike weights (w_A) that represent the relative probability of each model being correct were obtained. The Akaike

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[1] The comparison of models should be also considered in light of their overall complexity and not only on the basis of the number of free parameters. For instance, the Body-centered reference frame is defined as a cylindrical reference frame, whereas the Hand-centered reference frame is defined as a spherical reference frame. If we interpret these differences between models as additional parameters and we again apply the Akaike information criterion, the models' ranking remains unchanged with the Hand-centered weighted average model scoring best.

weights indicated that for all participants the Hand-centered weighted average model proved to be better than all the other models with a probability close to one. In the set of alternative models the Participant-dependent systematic error model was ranked as the second best, followed by the Systematic error model and by the Body-centered weighted average model. The Veridical model resulted as the least likely model in explaining the data.

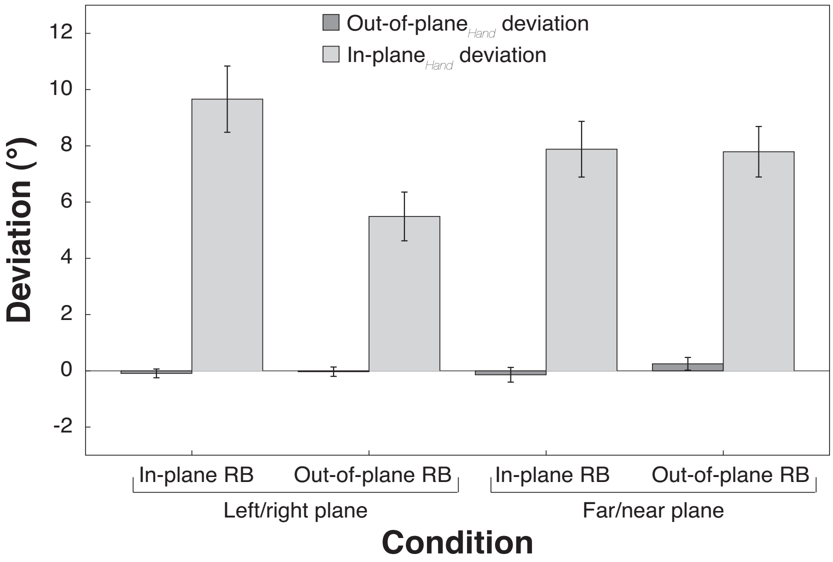

Figure 7. A bar chart that represents the in-plane$_{Hand}$ and the out-of-plane$_{Hand}$ signed deviations averaged over all participants subdivided into the conditions of plane (Left/right plane vs. Far/near plane) and the conditions of reference bar (RB) orientation (In-plane RB vs. Out-of-plane RB). The error bars indicate the standard errors of the mean (N = 192).

Hand-Centered Weighted Average Model

Given the fact that the Hand-centered weighted average model appears to account best for the data, subsequent steps will focus on more detailed analyses of the error patterns with respect to this model only. Figure 7 represents the signed in-plane$_{Hand}$ and the out-of-plane$_{Hand}$ deviations averaged over all participants and subdivided into the different conditions of plane (Left/right plane vs. Far/near plane) and reference bar orientation (In-plane reference bars vs. Out-of-plane reference bars). A multivariate repeated measure analysis of variance (MANOVA) showed no effect either of the plane or of the reference bar orientation, but indicated a significant interaction between the two factors ($F(2,6) = 39.766$, $p < .001$). Furthermore, follow-up univariate repeated measures ANOVAs with the significance level α lowered to .025 using the Bonferroni correction were performed separately for the two dependent measures. In the case of in-plane$_{Hand}$ deviations, a significant main effect was found for the factor of plane ($F(1,7) = 36.227$, $p < .023$) and an interaction effect between plane and reference bar orientation conditions ($F(1,7) = 33.147$, $p < .001$). For the out-of-plane$_{Hand}$ deviations, none of the factors or their interaction reached significance. The tests of between-subjects effects led to an interesting result: while participants differed significantly in in-plane$_{Hand}$ deviations ($F(1,7) = 76.018$, $p < .001$), their performance did not differ in out-of-plane$_{Hand}$ deviations.

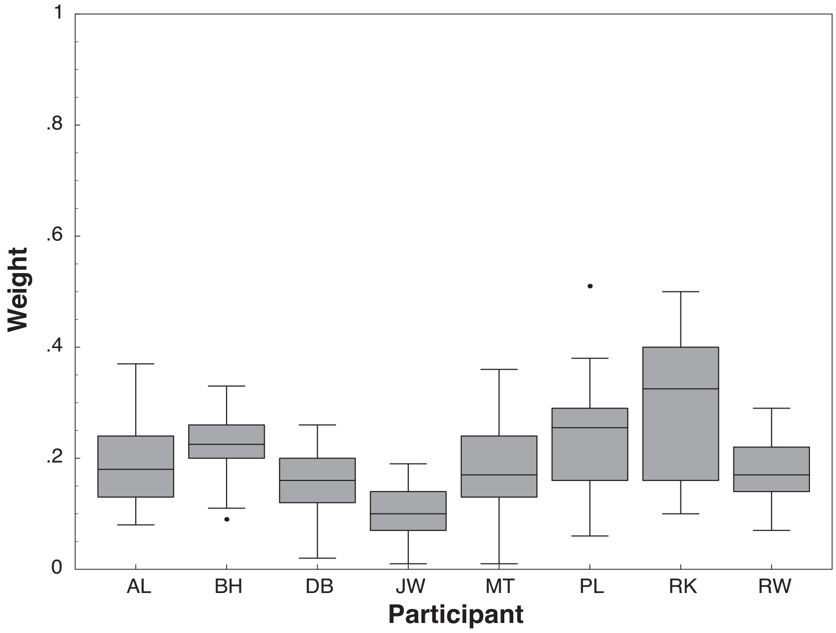

Figure 8. Box-and-whisker plot representing the statistical dispersion of the weighting factor that indicates the contribution of the hand-centered egocentric reference frame for each participant ($N = 24$). The boxes represent the interquartile range and the whisker lines include the non-outlying data points. Outliers (black dots) are defined as points beyond 3⁄2 the interquartile range from the edge of the boxes.

For each trial (that is, a set of eight bars that had to be oriented parallel to the reference bar) a weighting factor for the Hand-centered weighted average model was computed as explained in the Data analysis section. Thus, for each participant 24 weighting factors were obtained. The extents of the weighting factors sets' for each participant are displayed in Figure 8 by means of a box-and-whisker plot. Each weighting factors set is represented by a box that spans the distance between the second and the third quartile surrounding the median. Whisker lines extending above and below indicate the non-outlying data points. Outliers are defined as points beyond 3⁄2 the interquartile range from the edge of the box and are represented by the black dots. It is worthwhile observing that the medians of the weighting factors distributions differ among participants indicating specific contributions of the egocentric frame of reference linked to the hand. Moreover, the individual interquartile ranges used as a measure of the statistical dispersion attest relatively small variations of the weighting factors estimates within each participant. Additionally, the three repetitions (in temporal order) of all the experimental conditions were compared with each other to detect any changes in the weighting factor due to practice. These multiple paired t-tests were conducted on the data of each participant separately. The minimal level of significance retained was lowered to .017 (Bonferroni correction). No comparison led to a significant result ($p > .11$), thus, for every participant the average weighting factor stayed approximately stable over the three repetitions. Furthermore, the effects of the plane and reference bar orientation conditions on the weighting factor were tested by performing a repeated measures ANOVA. Similarly to the previous analysis no effect proved to be significant. These two analyses combined with the narrow interquantile ranges observable in Figure 8 provide fair evidence for the constancy of the weighting factor. It has to be noted that in a different analysis a single weight was obtained by fitting all the trials for each participant. These weights were almost identical to the average weights obtained in the previous analysis.

Discussion

In the present study, we researched haptic space perception of parallelity in three dimensions by considering different reference bar orientations and covering quite a large area of the frontal peripersonal space. Similar studies with a two-dimensional version of the parallelity matching task performed on the main orthogonal planes (horizontal, midsagittal, frontoparallel) have suggested that the deviations from veridicality are caused by a combined use of an allocentric and a biasing egocentric reference frame (Kappers, 2004, 2005, 2007; Kappers & Viergever, 2006; Volcic et al., 2007). These studies showed that a weighted average model that balanced the participant-dependent contributions of the two frames of reference efficiently described the experimental results. On the other hand, the identification of the origin of the egocentric reference frame was yet not conclusive. The findings of the present study extend the validity of the weighted average model to three-dimensional haptic perception of space and increase the evidence in support of a hand-centered egocentric reference frame.

We investigated the research question of whether systematic deviations occur also in three-dimensional haptic parallelity perception, by examining the errors under the three analyzing methods (Allo, Body and Hand methods). The extent of the errors made it evident that the participants' performance was physically unveridical, but the underlying structure of the deviations was undoubtedly characterized by a systematic error pattern. All the deviations occurred with regularity in specific directions and the sizes of the deviations were consistently scaled over the workspace reflecting the influence of a presumably unique mechanism. The three analyzing methods were adopted with the purpose of capturing these regularities in the deviations. On the basis of the hypothesis that presupposes a biasing influence of an egocentric frame of reference, the deviations were expected to cluster along the direction of the mismatch between the allocentric and the egocentric frame of reference. Specifically, the two-parameter analyzing method that best encapsulates the systematicity in the deviations should evince itself as the method that comprises almost the entirety of the total deviation in one parameter, and the contingent residual part in the second parameter orthogonal to the first one. In fact, the analyzing method that assumed the hand as the origin of the egocentric reference frame convincingly satisfied these assumptions. The first error parameter, that is, the in-plane$_{Hand}$ deviation, accounted for most of the total deviation. The in-plane$_{Hand}$ deviations were characterized by a common direction and by a participant-dependent magnitude of the deviations in agreement with the hypothesis of a biasing hand-centered egocentric frame of reference. Regarding the second error parameter, the out-of-plane$_{Hand}$ deviation, the deviations were relatively small and the range of these deviations was centered on zero indicating that the out-of-plane$_{Hand}$ deviations were actually clustered around the plane defined by the mismatch between the allocentric and the hand-centered egocentric reference frame. On the contrary, the other two analyzing methods were less precise in capturing the directional systematicity in the deviations. This was mainly proven by the fact that the magnitudes of the unsigned deviations (tilt vs. slant for the Allo analyzing method, and out-of-plane$_{Body}$ vs. in-plane$_{Body}$ deviations for the Body analyzing method) were less differentiable than for the Hand analyzing method.

Given the fact that the aforementioned results gave a strong indication about the directionality of the deviations that is coherent with the hypothesis of a crucial involvement of a biasing hand-centered reference frame, it was of deep interest to validate the Hand-centered weighted average model also with respect to the expected extents of the deviations. For this purpose, the five considered models were compared by means of Akaike's information criterion and the average absolute deviations between each model and the data. Since Akaike's information criterion evaluates both the accuracy of a model and the costs of including extra parameters, it was advantageous to compare the different models through this method, as it determines the probability of each model being correct given the data. On the other hand, the analysis of the average absolute deviations evaluated the different models in a quantitative way by specifying the average discrepancy between a model and the data. The Hand-centered weighted average model proved to be the model with the highest probability of being correct among the considered models (despite the cost of additional parameters), and, at the same time, the model that most closely resembled the data. This means that the settings were actually biased towards the hand-centered egocentric frame of reference and the extent of the deviations was dependent on the amount of the contribution of the hand-centered egocentric frame of reference. The Hand-centered weighted average model, therefore, explained the direction and the magnitude of the deviations, and, moreover, accounted for the inter-participant variability. In contrast, each of the four alternative models was characterized by specific drawbacks. The Veridical model failed to predict the systematic error patterns, because it was based on the assumption that no major deviation from the physically parallel settings would be observed. In the case of the Systematic error model, although the accuracy of the model improved, mainly because the general direction of the deviations was identified, the model was unable to capture the systematic variations in the magnitude of the deviations over the workspace and the inter-participant differences in the direction and in the magnitude of the deviations. The Participant-dependent systematic error model suffered from similar problems, although the accuracy was improved by the addition of a parameter that accounted for inter-participant heterogeneities. As for the Body-centered weighted average model, the inaccuracy was due to the fact that deviations were expected to occur in the plane perpendicular to the body-midline only and no prediction was made about any swerve from this plane. This characteristic of the model induced error in the predictions to such an extent that it proved to be even less accurate than the descriptive models predicting position-invariant deviations. A model that fixes the anchor point of the egocentric frame of reference to the body would probably gain in accuracy if, instead of defining the body-midline as the origin, it defined as the origin a specific point location on the body-midline. This problem was obviously not taken into consideration in the studies conducted on two-dimensional planes (Kaas & van Mier, 2006; Kappers, 2007) and any proposition about the location of the body-origin would be at this point highly speculative.

In light of the Hand-centered weighted average model being the most corroborated model, the deviations according to the Hand analyzing method were further analyzed with respect to the different conditions of plane and reference bar orientation. According to the model, some differences in the magnitude of the in-plane$_{Hand}$ deviations were expected to occur depending on the degree to which the reference bar orientation was aligned with respect to the direction of the mismatch between the allocentric and the hand-centered egocentric frame of reference. In the limit case, if the reference bar were orthogonal to the plane defined by the two reference frames, the magnitude of the in-plane$_{Hand}$ deviation would approach zero. On the other hand, we expected negligible fluctuations in the magnitude of the out-of-plane$_{Hand}$ deviations in all conditions. The comparison of the different conditions showed, in fact, minor variations in the magnitude of the in-plane$_{Hand}$ deviations in accordance with our expectations and no effect of the different condition on the out-of-plane$_{Hand}$ deviations. In addition, in an overall analysis of the conditions it was reconfirmed that whereas participants differed in in-plane$_{Hand}$ deviations, due to the participant-dependent contributions of the egocentric reference frame, they all revealed the same average out-of-plane$_{Hand}$ deviations scattered around zero.

One of the assumptions of the Hand-centered weighted average model is that the inter-participant differences in performance reflect the strength of the biasing influence of the hand-centered egocentric reference frame. The model will gain in its descriptive capabilities if the weighting factor specific for each participant that expresses the biasing influence proves to be relatively stable in different conditions and over repetitions of the same trial. We have shown that the weighting factor could only vary in a limited range for each participant. Therefore, we can confidently assert that each participant was characterized by a specific weighting factor modulating the contributions of the allocentric and the hand-centered egocentric reference frame. Moreover, it is worth observing that although the average weighting factors differed among participants, they all fell in the range between .1 and .3. If we define a continuum between the reference frame fixed to the space and the one fixed to the hand, participants' performance shifted on average by 19.6% from the allocentric reference frame to the one fixed to the hand. This estimate is in agreement with the 23.8% shift towards the egocentric reference frame found by Kappers (2007) in the two-dimensional parallelity task. Moreover, in a slightly different task Flanders and Soechting (1995) showed that when participants were asked to orient the hand in a frame of reference fixed in space, they also showed a tendency of approximately 25% towards the use of a frame of reference fixed to the arm.

In general, we propose that a hand-centered and an allocentric reference frame operate synergistically in the construction of the haptic representation of space. Coding object's orientation with respect to the hand is of vital importance while grasping objects in everyday life and, therefore, an egocentric reference frame centered on the hand might have a central role in the interaction with objects. While it may seem restrictive to consider only an egocentric reference frame fixed to the hand, we have provided convincing evidence that this framework successfully accounts for the deviations observed in the three-dimensional haptic parallelity task. A more comprehensive model should certainly regard the hand-centered egocentric reference frame as part of a hierarchically organized structure of egocentric reference frames interconnected with an allocentric reference frame. The spatial processing therefore appears to be based on multiple spatial representations among which those that are relevant for a specific task emerge as the dominant representations. This view has its clear advantages since the maintenance of distributed representations of many reference frames can be available depending on the requirements of a specific behavior. A consequential limitation is given by the fact that resulting behavior can be a product of different co-influencing representations that can bias the optimal solution for the required behavior. This hypothesis of multiple and interacting spatial representations is accordant with a more general framework in visuomotor literature (Carrozzo & Lacquaniti, 1994; Carrozzo et al., 2002; Cohen

& Andersen, 2002; Soechting & Flanders, 1992, 1993). The existence of multiple and coexisting levels of representation is thus supported by a plethora of psychophysical and neurophysiological studies (for a review, see Battaglia-Mayer et al., 2003). Therefore, we presume that the combination of different reference frames might be a general characteristic of spatial processing independent of the specific sensory modality.

In summary, we showed that participants systematically deviate from veridicality when asked to construct a field of parallel bars in three-dimensional space. The systematic patterns of deviations are efficiently captured by the Hand-centered weighted average model that presupposes a biasing, thus interfering, impact of an egocentric reference frame fixed to the hand on the allocentric frame of reference. The participant-specific weighting factor accounts for the inter-participant variability in the magnitude of the deviating behavior. Consequently, these results strengthen the hypothesis that haptic spatial processing bases its properties in the interaction of a plurality of reference frames.

Appendix

This appendix explains the method by which the different models were compared. The performance of the model was compared with those of alternative models by analyzing for each model the goodness-of-fit relative to the number of parameters by applying Akaike's information criterion (AIC) with sample-size correction ($\mathrm{AIC_c}$). This method answers the question about which model best approximates reality given the set of measured data. This goal can be accomplished by minimizing the loss of information. Kullback and Leibler (1951) addressed this issue and developed a measure of loss that was later adopted by Akaike (1973). For details about this approach see Burnham and Anderson (2002). The measure of information loss comprises a term estimating the goodness-of-fit to a set of data (e.g., sum-of-squares) and a term estimating the effect of the number of parameters (e.g., complexity) according to the principle of parsimony. Akaike's information criterion corrected for sample-size was evaluated as:

$$\mathrm{AIC_c} = n\ln\left(\frac{SS}{n}\right) + 2k + \frac{2k(k+1)}{n-k-1}, \tag{3}$$

where n is the number of data, SS is the sum-of-squares, and k is the number of model parameters plus one. In general, the smaller the value of $\mathrm{AIC_c}$ the better the model performs. Different models (r) from a set of models (R) can be ranked on their performance by comparing $\mathrm{AIC_c}$ values for each i-th model to a comparison model (superscript M):

$$\Delta\mathrm{AIC}_c^i = \mathrm{AIC}_c^i - \mathrm{AIC}_c^M. \tag{4}$$

These $\Delta\mathrm{AIC_c}$ values were then exponentially transformed to compute Akaike weights (w_A) that provide a measure of the strength of evidence for each model, and represent the relative probabilities of each model being correct among the whole set of R candidate models:

$$w_A^i = \frac{e^{-\frac{1}{2}\left(\Delta\mathrm{AIC}_\mathrm{c}^i\right)}}{\sum_{r=1}^{R} e^{-\frac{1}{2}\left(\Delta\mathrm{AIC}_\mathrm{c}^r\right)}}. \tag{5}$$

Chapter 4

Differential Effects of Non-Informative Vision and Visual Interference on Haptic Spatial Processing

Abstract

The primary purpose of this study was to examine the effects of non-informative vision and visual interference upon haptic spatial processing, which supposedly derives from an interaction between an allocentric and an egocentric reference frame. To this end, a haptic parallelity task served as baseline to determine the participant-dependent biasing influence of the egocentric reference frame. As expected, large systematic participant-dependent deviations from veridicality were observed. In the second experiment we probed the effect of non-informative vision on the egocentric bias. Moreover, orienting mechanisms (gazing directions) were studied with respect to the presentation of haptic information in a specific hemispace. Non-informative vision proved to have a beneficial effect on haptic spatial processing. No effect of gazing direction or hemispace was observed. In the third experiment we investigated the effect of simultaneously presented interfering visual information on the haptic bias. Interfering visual information parametrically influenced haptic performance. The interplay of reference frames that subserves haptic spatial processing was found to be related to both the effects of non-informative vision and visual interference. These results suggest that spatial representations are influenced by direct cross-modal interactions; inter-participant differences in the haptic modality resulted in differential effects of the visual modality.

Volcic, R., van Rheede, J. J., Postma, A., & Kappers, A. M. L. (in press). Differential effects of non-informative vision and visual interference on haptic spatial processing. *Experimental Brain Research*, doi: 10.1007/s00221-008-1447-0.

Introduction

Information about the world reaches us through more than one sense. The integration of input from different sensory modalities is, therefore, an important aspect in forming a representation of objects and the surrounding environment. A single object may generate different sensory inputs across multiple sensory channels. Hence, strong interactions between the modalities shape the integrated percept of the object. However, different information can also originate from sources extrinsic to the object. For instance, information that belongs to the surrounding environment could also be relevant for perception of the object at issue. In this case, when information across modalities is not explicitly associated, the integration of information is possible but certainly not a necessary consequence. If and how these latter integration processes occur is not yet clear. To tackle these questions we evaluated the interaction between the processes involved in haptic perception of space and the effects of non-informative vision and visual interference. Haptic spatial tasks usually induce very large biases and are, therefore, especially suitable for the study of these effects.

Haptic spatial processing, as a unimodal perceptual experience, has been shown to be prone to substantial systematic deviations from veridicality (e.g., Blumenfeld, 1937; Henriques & Soechting, 2005; Lederman et al., 1987; von Skramlik, 1934a, 1934b). The haptic perception of space has been analyzed especially through the use of the haptic parallelity task (e.g., Kappers, 1999; Kappers & Koenderink, 1999). In this task blindfolded participants were instructed to rotate a test bar in such a way that they felt it to be parallel to a reference bar that was located at a different position. A methodical series of studies has mapped the magnitude and direction of deviations occurring at different spatial locations (Kappers, 1999; Kappers & Koenderink, 1999), different planes (Hermens et al., 2006; Kappers, 2002; Volcic et al., 2007) and even in three dimensions (Volcic & Kappers, 2008). The systematic deviations observed in this variety of experimental conditions were reliably accounted for by supposing a biasing effect of hand orientation as the origin of the error patterns (Kappers, 2004; Kappers, 2005; Kappers & Viergever, 2006, Volcic et al., 2007). Note that the concept of parallelity is implicitly defined with respect to the environment, that is, with respect to an allocentric reference frame. Participants are thus required to transform the spatial information in this reference frame. Therefore, it was proposed that haptic spatial processing could be described as the interplay of an egocentric reference frame fixed to the perceiver's hand and an allocentric reference frame, reflecting the spatial properties of the surrounding environment. A similar hypothesis has been sustained also by numerous studies in visuomotor literature (e.g., Battaglia-Mayer et al., 2003; Carrozzo & Lacquaniti, 1994; Cohen & Andersen, 2002; Soechting & Flanders, 1992, 1993). Interestingly, in the haptic parallelity task the same error patterns were found in both unimanual and bimanual experiments suggesting a common origin of the error patterns. An influence of an egocentric reference frame fixed to the perceiver's hand is actually not surprising; inevitably, the initial stages of haptic spatial processing are tuned to the part of the body that is directly in contact with the environment, in our case, the hand. The reference frames hypothesis was implemented in a weighted average model that balanced the contributions of an egocentric and an allocentric reference frame (Kappers, 2007; Volcic & Kappers, 2008). Importantly, this model could account for the variability in the magnitude of the deviations (ranging up to 90°) observed among participants (Kappers, 2003). The greater deviations from veridicality shown by some participants were interpreted as the consequence of a more heavily weighted egocentric reference frame, whereas smaller deviations indicated the participants' stronger reliance on the allocentric reference frame. In line with this explanation is also the effect of temporal delay in the haptic parallelity task (Zuidhoek et al., 2003). Performance improved when a delay was introduced between the perception of a reference bar and the setting of the test bar. This improvement was interpreted as a reinforcement of the contribution of the allocentric reference frame as also suggested by other studies (e.g., Rossetti & Régnier, 1995; Rossetti et al., 1996).

A research area complementary to the unimodal studies of haptic spatial processing has addressed the issue of the influence of additional sources of information such as, for instance, vision. Newport et al., (2002) reported that non-informative vision modifies the performance in the haptic parallelity task. Non-informative vision was referred to as vision of the near space without any visual input that is directly relevant to the task at hand. Deviations were still systematic, but they were reduced in comparison to the condition in which no extra visual source of information was available. This effect could be interpreted within the weighted average model as the consequence of an enhancement of the influence of the allocentric reference frame. Non-informative vision supplements the available information about the environment and thus reduces the biasing influence of the egocentric reference frame, resulting in smaller deviations. A further effect studied in combination with the non-informative vision effect was ascribed to the head- and eye-orienting mechanisms (Zuidhoek et al., 2004). Orienting the gaze towards the region of space where the reference bar was located yielded smaller deviations than orienting it towards the test bar. This effect ensued independently of the non-informative vision effect. Unfortunately, the reference bar in this study was always located in the left hemispace and this might have confounded the effect of orienting direction with a hemispace effect. The question of whether orienting mechanisms improve tactile processing has been addressed especially in tactile detection and discrimination studies. The impact of the orienting mechanisms on tactile processing is, however, still undecided (e.g., Driver & Grossenbacher, 1996; Honoré et al., 1989; Kennett et al., 2001; Pierson et al., 1991; Tipper et al., 1998).

Haptic spatial processing has also been recently studied in combination with interfering visual information (Kaas et al., 2007). A bar was visually presented on a screen and the participant had to simultaneously perform the haptic parallelity task. The visual bar was either in a congruent or incongruent orientation with respect to the haptic reference bar. As a result, the deviations were modulated by the degree to which the visual information of the object orientation was incongruent with the haptic information. The effect of visual interference was observed despite the fact that visual and haptic information were provided in different spatial locations and different planes. Although participants received visual input, this stimulation lacked any information about the surrounding environment and therefore no effect of non-informative vision was observed. Kaas et al. (2007) concluded that the visual input was combined with the haptic input despite the incongruence between visual and haptic information and the explicit instruction to ignore the visual information.

The main aim of this paper was to pinpoint the effects of non-informative vision and visual interference in relation to the inter-participant differences that are common in haptic spatial processing. The effects of both non-informative vision and visual interference require some sort of integration between haptic and visual information in order to occur. Therefore, we might hypothesize that the participant-dependent tendency in haptics to rely more either on the allocentric or on the egocentric reference frame possibly interacts with the degree to which the two effects arise. The participant-dependent reliance on a specific reference frame could either induce or prevent the visuo-haptic integration. Consequently, it would result in stronger or weaker non-informative vision and visual interference effects. Those participants that are characterized by a more egocentric performance would profit more by integrating the additional visual information. The integration processes would then counterbalance the biasing influence of the egocentric reference frame and improve performance. On the other hand, their haptic egocentric bias could also be so prevailing that it would result in a stronger or weaker suppression of any visual information. Performance would then be unaffected by these additional sources. The way the allocentric and the egocentric reference frames are weighted has been shown to largely differ between participants. If we define a continuum between the reference frame fixed to the space and the egocentric reference frame, participants' performances can be located all the way along this range. One example of a clear individual difference concerns also a gender effect: males on average show a weaker bias of the egocentric reference frame than females (Kappers, 2003; Zuidhoek et al., 2007). However, Kappers (2003) showed that male and female distributions of performances were highly overlapping and that the inter-participant differences were larger than the difference between genders. Therefore, a gender-based distinction might oversimplify the problem by not considering a more general gender-independent mechanism that could be at the origin of haptic spatial processing. If a relation exists between the weighting of reference frames in haptic spatial processing and the integration of visual information, we predicted a modulation of the size of the effects in relation to the participant-dependent weighting of reference frames.

In the first experiment we measure the baseline deviations in the haptic parallelity task to determine the degree to which each participant is biased by the egocentric reference frame. This task is then used in the two subsequent experiments as a tool to study the effects of non-informative vision and visual interference. In all the experiments we contrast a gender-based subdivision of the data with a description of the data that takes into account the full spectrum of inter-participant differences. In the second experiment, the addition of non-informative vision to the haptic parallelity task is presumed to improve the performance of the participants. Whether the improvement depends on the size of the biasing influence of the egocentric reference frame is one of the central questions of this paper. Besides this, our interest also concerned how the orienting mechanisms in the non-informative vision experiment interact with the presentation of haptic information in a specific hemispace. In the third experiment, the performance in the haptic spatial task was addressed in combination with interfering visual information. Incongruent visual information about the orientation of the object is supposed to parametrically bias the performance on the haptic parallelity task in the direction of the mismatch between haptic and visual inputs. The question again was whether the influence of visual interference is related to the tendency to rely more heavily on either the allocentric or the egocentric frame of reference.

Materials and Methods

Participants

Twenty undergraduate students (ten males and ten females) were recruited in this research and were remunerated for their efforts. Participants had normal or corrected-to-normal vision and normal haptic, somatosensory and motor functioning. None of the participants had any prior knowledge of the experimental design and the tasks. Handedness was assessed by means of a standard questionnaire (Coren, 1993). One participant was left-handed, five participants could be considered ambidextrous, expressing only a slight preference for one or the other hand, and the other 13 participants were right-handed.

Apparatus and Stimuli

The set-up consisted of a table (150 × 75 × 75 cm) on which two iron plates (30 × 30 cm) were positioned on either side of the participant's midsagittal plane. The iron plates were covered with a plastic layer on which a protractor with a radius of 10 cm was printed. The centers of the two protractors were 120 cm apart and 15 cm from the long table edge. The participant was seated in front of the table on a stool, which was adjusted so that the shoulders of different participants were always at the same height (110 cm). An aluminum bar, with an axle in the middle, was inserted in the center of each protractor and could be rotated freely. Small magnets were attached under the bar to prevent accidental rotations. Two bars with a length of 20 cm and a diameter of 1 cm were used as the test and reference bars. The bars had an arrow-shaped end on one side that allowed the reference bar orientation and the test bar orientation to be read off with an accuracy of 0.5°. The bars were hidden from view by a wooden board 15 cm above the bars, and participants were covered up to the neck by a sheet attached to this board in order to prevent orientation cues from the orientation of their own body parts (see Figure 1). Two additional iron plates were positioned on the top of the board exactly above the other iron plates. These iron plates were covered with black cardboard discs (radius of 22.5 cm) that prevented participants from seeing the protractors and avoided a direct frame of reference for the visual stimulus. A hole in the center of the discs allowed the insertion into the iron plate of a round magnet marker (radius of 1.25 cm) or of a bar depending on the experimental condition.

Four oblique reference orientations were tested, namely 22.5°, 67.5°, 112.5° and 157.5°. The 0° orientation was aligned along the left–right axis of the table and an increase in degrees signifies a rotation in the counterclockwise direction. The reference bar could be positioned at either the left or the right side of the set-up, that is, in the left or the right hemispace. The test bar was located on the opposite position and presented in a random orientation. Both these bars were hidden below the wooden board and were explored only by touch.

This study consists of three experiments: a *Haptic baseline* experiment, a *Non-informative vision* experiment and a *Visual interference* experiment. In the haptic baseline experiment participants completed 4 reference bar orientations (22.5°, 67.5°, 112.5° and 157.5°) × 2 reference bar positions (left hemispace vs. right hemispace) × 3 repetitions = 24 trials. In the non-informative vision experiment participants completed 4 reference bar orientations (22.5°, 67.5°, 112.5° and 157.5°) × 2 reference bar positions (left hemispace vs. right hemispace) × 2 gazing directions (towards either the reference or the test bar) × 3 repetitions = 48 trials. In the visual interference experiment participants completed 4 reference bar orientations (22.5°, 67.5°, 112.5° and 157.5°) × 2 reference bar positions (left hemispace vs. right hemispace) × 5 visual incongruencies (-40°, -20°, 0°, 20°, 40° compared to the haptic orientation) × 3 repetitions = 120 trials. In total, each participant completed 192 trials. The order of trials within each experiment was random and different for each participant, whereas the order of the three experiments was the same for all participants.

Procedure

Participants had to perform a bimanual parallelity task. The experimenter set the reference bar and announced to the participant which bar served as the reference bar for this trial. The participants were instructed to rotate the test bar in such a way that they felt it to be parallel to the reference bar. Both bars were touched simultaneously for the whole duration of each trial; the left hand always touched the left bar, the right hand the right bar. Participants had 10 s to explore the bars and orient the test bar, which appeared to be a more than adequate amount of time. An electronic digital timer measured the time, with a beep signaling when it had run out. Participants then removed their hands from the set-up and after the experimenter noted down the orientation of the test bar, the next trial commenced. No feedback was given about their performance.

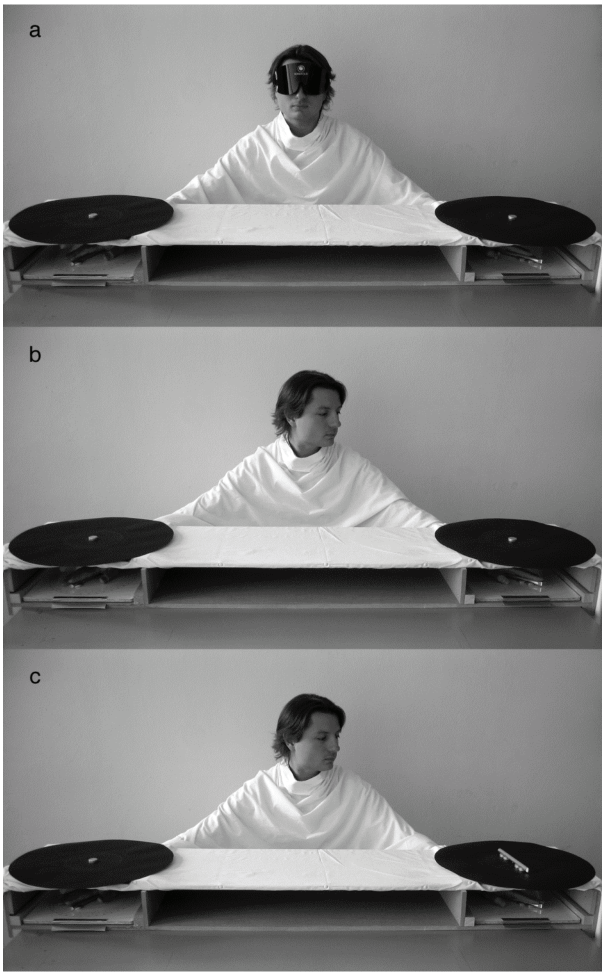

Figure 1. Frontal views of the set-up in the three experiments. a Haptic baseline experiment. b Non-informative vision experiment. c Visual interference experiment.

In the haptic baseline experiment participants were blindfolded and asked to orient their head in alignment with the midsagittal plane (see Figure 1a). Participants kept this posture for all the trials of this experiment. The non-informative vision experiment was essentially similar, but the blindfold was removed and participants were asked to orient their head and direct their gaze to a marker in the center of the black cardboard discs above either the reference or the test bar (see Figure 1b). The experimenter, therefore, not only announced which bar would serve as the reference bar, but also in which direction participants should orient their head and direct their gaze. The visual interference experiment was similar to the latter, but instead of markers, bars identical to those used for the haptic exploration were positioned in the center of the black cardboard discs (see Figure1c). In this experiment, the visual bar was always positioned above the haptic reference bar. For each trial, the visual bar was set to deviate -40°, -20°, 0°, 20° or 40° with respect to the reference bar below. Participants were told to always orient their head and direct their gaze towards the visual bar. Additionally, participants were told that the visual bar may or may not be aligned with the haptic bar below, and were explicitly asked, therefore, to use the haptic bar as a reference, as they did in the previous two experiments.

Breaks were introduced between experiments, and the visual interference experiment was interrupted by two short breaks to prevent fatigue. Participants took on average 3 h to complete all three experiments.

Data Analysis

Previous studies using the haptic parallelity task have established that the deviations vary in a systematic way. Deviations occur in a counterclockwise direction when the reference bar is on the right of the test bar, whereas they occur in a clockwise direction when the reference bar is on the left of the test bar. Such deviations are defined as the orientation of the left bar minus the orientation of the right bar; therefore, the deviation specifies both the direction and the magnitude of the error. Positive values correspond to deviations in the expected direction, and negative values to deviations in the opposite direction. Suppose that the left bar is set at 112.5° and the right bar at 70°, then the resulting deviation corresponds to 42.5° that is in accordance with the direction found in previous studies. The orientation of the visual bar was similarly defined: a positive value corresponds to a rotation in the direction of the expected haptic deviation of the test bar, whereas a negative value corresponds to a rotation in the opposite direction. Suppose that the visual bar is set at 132.5° above the previously mentioned left haptic bar, given that the rotation of the bar is in the opposite direction to the expected direction, the orientation of the visual bar is defined to be -20°.

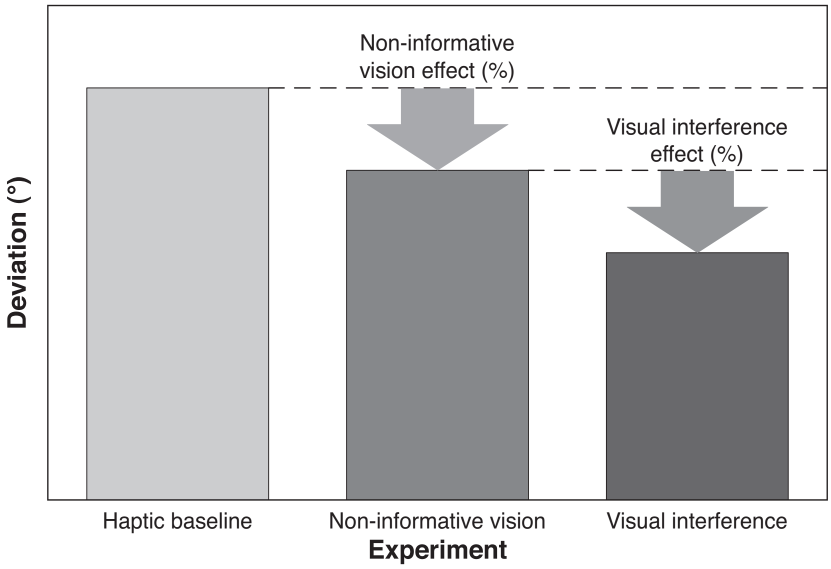

Figure 2. Representation of the calculation of the non-informative vision effect and the visual interference effect. The non-informative vision effect was expressed as a percent change between the haptic baseline and the non-informative vision experiments. The visual interference effect was expressed as a percent change between the non-informative vision and the visual interference experiments. Note that the changes between experiments are not necessarily negative, so in fact the arrows might point upwards.

To isolate the pure effects of non-informative vision and visual interference we followed the procedures represented in Figure 2. Specifically, the effect of non-informative vision was expressed as the percent change between the haptic baseline experiment and the non-informative vision experiment. For each participant individually the percent changes of the non-informative vision conditions were calculated with respect to the average deviation of the haptic baseline experiment. Therefore, a negative percent change indicates a decrease in the deviation from veridicality and conversely a positive percent change indicates an increase in the deviation from veridicality. Similarly, the effect of visual interference was expressed as the percent change between the non-informative vision experiment and the visual interference experiment. For each participant individually the percent changes of the visual interference conditions were calculated with respect to the average deviation of the non-informative vision experiment. Negative and positive percent changes indicate decreases and increases in the deviations from veridicality, respectively.

In the repeated measures analyses on the data of the visual interference experiment, the assumption of sphericity was tested, and if necessary the degrees of freedom were corrected using the

Greenhouser-Geisser ε-correction. The minimal level of significance retained was .05. In all the follow-up repeated measures analyses and in the pair-wise comparisons the Holm's procedure (Holm, 1979) was applied to lower the minimal level of significance. Outlier analyses were conducted on the data used in the regression analyses.

The focus of our study was mainly directed to the effects of non-informative vision and visual interference. Consequently, the reference bar orientation was not included as a statistical factor in the data analyses. Different orientations were included both to increase the variety of stimuli and to enlarge the data set.

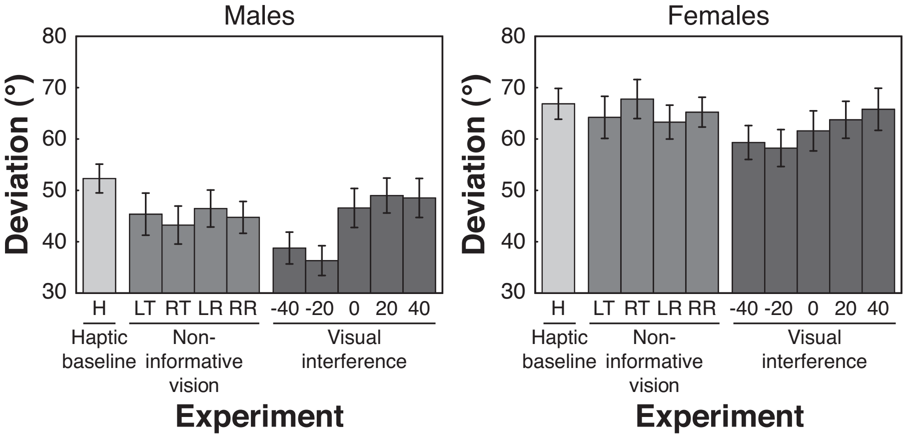

Figure 3. The bar charts represent the deviations in the haptic baseline, the non-informative vision and the visual interference experiments. Deviations in the different conditions are shown for the latter two experiments. The left bar chart presents the male group data and the right bar chart presents the female group data. The error bars indicate the standard error of the mean. H – haptic; LT – gazing direction to the left hemispace towards the test bar; RT – gazing direction to the right hemispace towards the test bar; LR – gazing direction to the left hemispace towards the reference bar; RR – gazing direction to the right hemispace towards the reference bar; -40, -20, 0, 20, 40 – misalignments between the haptic and visual bars.

Results

The bar charts in Figure 3 show the average deviations male and female participants made in the haptic baseline, the non-informative vision and the visual interference experiments. Deviations in the non-informative vision and visual interference experiments are separated for conditions. We ran a repeated measures ANOVA with experiment as the within-subject factor and gender as the between-subject factor as a crude comparison between experiments. Within-experiment conditions were blocked. The experiment factor was significant (*F*(2,36) = 9.964, $p < .001$), whereas the interaction between experiment and gender was not significant (*F*(2,36) = 1.67, $p = .203$). On the other hand, the gender factor was significant (*F*(1,18) = 16.702, $p < .001$). Subsequent pair-wise comparisons showed that performance in the haptic baseline experiment was worse than performance in both the non-informative vision (*t*(19) = 3.155, $p < .01$) and visual interference experiments (*t*(19) = 3.513, $p < .01$). No significant difference was found between the latter two experiments (*t*(19) = 1.755, $p = .098$). Separate follow-up repeated measures ANOVA were conducted for the male and female groups. The factor experiment was significant for both the male and female groups (*F*(2,18) = 5.881, $p < .05$, and *F*(2,18) = 5.627, $p < .05$, respectively). However, pair-wise comparisons showed a different pattern for the two groups. The male group performed better in the non-informative vision than in the haptic baseline experiment (*t*(9) = 3.349, $p < .05$). No significant difference was found between the visual interference experiment and the non-informative vision experiments (*t*(9) = .484, $p = .64$). The comparison between the haptic baseline experiment and the visual interference experiment just failed to reach significance (*t*(9) = 2.504, $p = .068$). On the other hand, the female group did not show any significant improvement in the non-informative vision experiment with respect to the haptic baseline experiment (*t*(9) = 1.173, $p = .271$). The comparisons between the haptic baseline and visual interference experiments, and between the non-informative vision and visual interference experiments just failed to reach significance (*t*(9) = 2.65, $p = .052$, and *t*(9) = 2.922, $p = .051$).

Further analyses on the single experiments with a more careful attention on the different conditions within each experiment and especially on the pure effects of non-informative vision and visual interference are presented below.

Haptic Baseline Experiment

The bar chart in Figure 4 shows the distribution of deviations among participants in the haptic baseline experiment. Light-colored bars represent male participants, whereas dark-colored bars represent female participants. It is evident that all participants significantly and systematically deviated from veridicality, although the magnitude of the deviations is clearly participant-dependent. A repeated measures ANOVA with reference bar position (left hemispace vs. right hemispace) as the within-subjects factor and gender as the between-subject factor showed that there was neither an effect of reference bar position (*F*(1,18) = .299, $p = .591$) nor an interaction between reference bar location and gender (*F*(1,18) = .143, $p = .709$). On the other hand, the gender factor was significant (males: 52.3° ± 2.8° *SEM*; females: 66.8° ± 3° *SEM*; *F*(1,18) = 12.248, $p < .005$); on average male participants were characterized by smaller deviations than female participants.

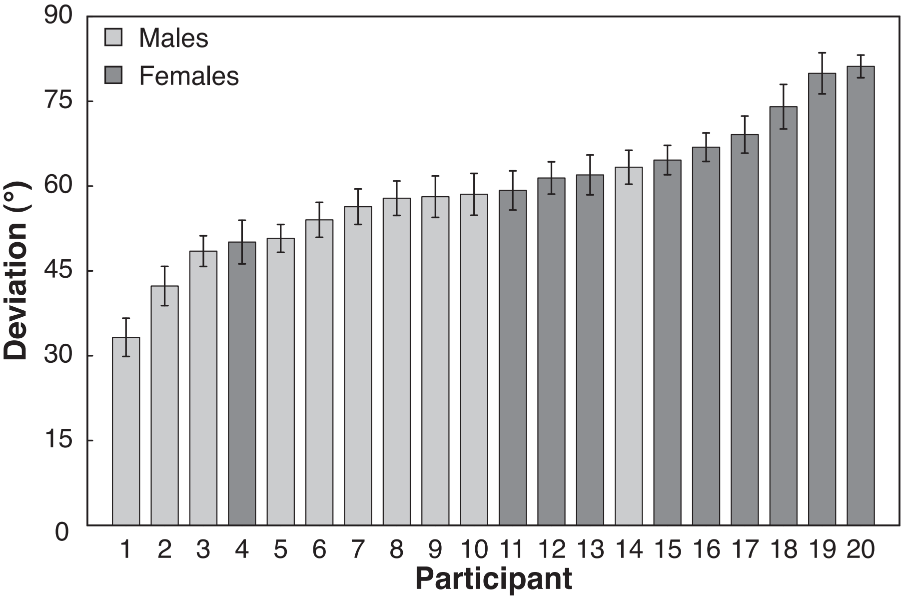

Figure 4. Haptic baseline experiment. Bar chart of the distribution of deviations from veridicality among participants. The error bars indicate the standard error of the mean.

Non-Informative Vision Experiment

In the non-informative vision experiment the percent changes for the separate conditions with respect to the haptic baseline experiment are shown in Figure 5. The factors of reference bar position (left hemispace vs. right hemispace) and gazing direction (towards either the reference or the test bar) were analyzed in a repeated measures ANOVA with gender as a between-subjects factor. The factors of reference bar position ($F(1,18) = .139$, $p = .714$) and gazing direction ($F(1,18) = .09$, $p = .767$) were not significant. No interaction reached significance ($.014 < F(1,18) < 1.816$, $p > .195$) except for the interaction between reference bar position and gender ($F(1,18) = 5.055$, $p < .05$), but follow-up repeated measures ANOVAs separated by gender did not reveal any difference between hemispaces ($F(1,9) = 1.837$, $p = .208$, and $F(1,9) = 3.296$, $p = .103$, for the male and female group, respectively). The difference between genders was significant (males: -14.7% ± 4.7% *SEM*; females: -2.7% ± 2.4% *SEM*; $F(1,18) = 5.06$, $p < .05$); on average the non-informative vision effect was smaller for females than males. Follow-up repeated measures ANOVAs on the gazing direction factor, but conducted separately on the male and female groups, did not reveal any significant effect ($.448 < F(1,9) < 1.073$, $p > .327$). Consequently, data were grouped among the conditions of reference bar position and gazing direction. Simple two-tailed t-tests conducted separately on the male and female groups were run to check if non-informative vision actually decreased the magnitude of the deviations. For the male group, the non-informative vision effect was significantly different from zero ($t(9) = 3.097, p < .05$). On the contrary, the non-informative vision effect failed to reach significance for the female group ($t(9) = 1.119, p = .292$).

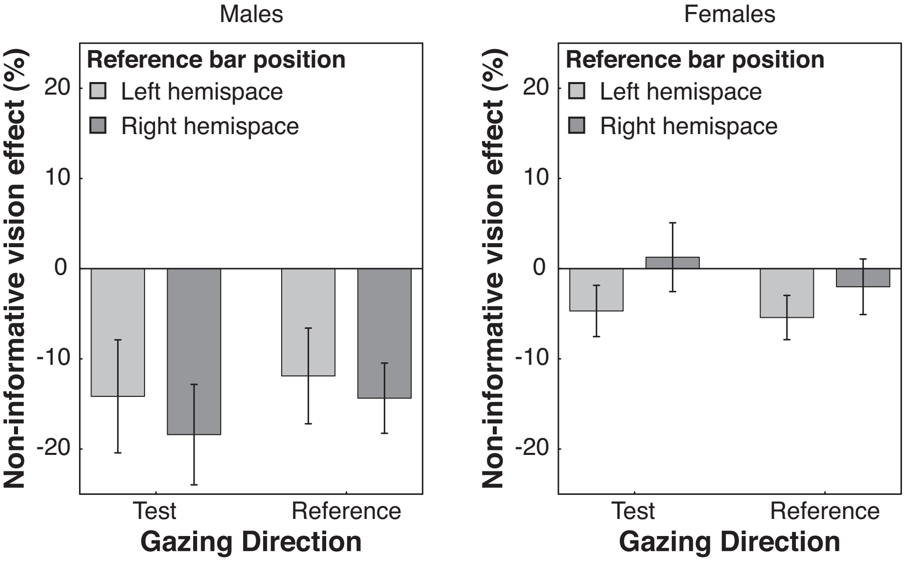

Figure 5. Non-informative vision experiment. The bar charts represent the non-informative vision effect for the conditions of gazing direction and reference bar position. The left bar chart presents the male group data and the right bar chart presents the female group data. The error bars indicate the standard error of the mean.

To further explore the non-informative vision effect we considered the magnitude of the effect as a function of the average haptic deviation and gender by conducting a stepwise regression analysis for factor selection. We decided on a significance level of .05 in order to determine which factors to include in the models, and a level of .1 in order to determine which to remove. The gender factor did not produce a significant improvement of the regression model; therefore, it was removed from the analysis. On the other hand, we found that the average haptic deviation was a significant predictor of the non-informative vision effect ($F(1,18) = 4.507, p < .05$). The non-informative vision effect (percent change) could be expressed as:

$$-39 + .5 * \text{average haptic deviation } (r = .45).$$

Therefore, in the range of interest the larger the average haptic deviation was, the smaller the non-informative vision effect tended to be (see Figure 6).

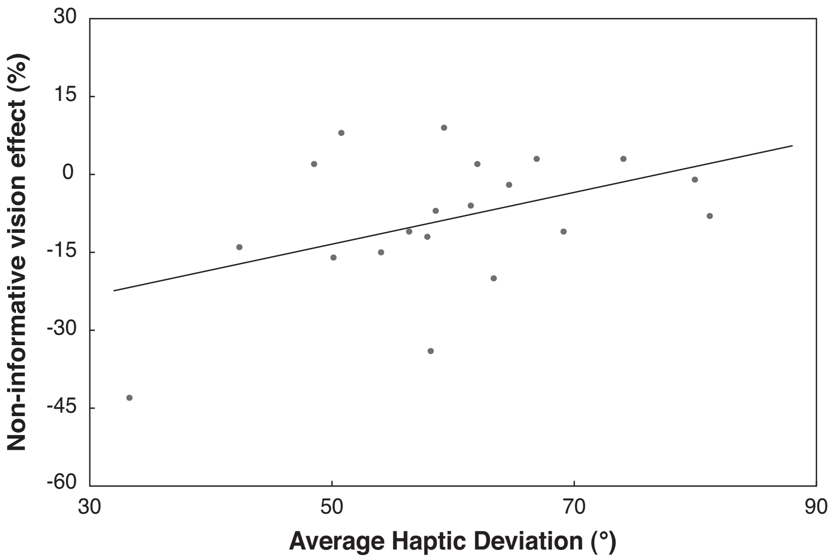

Figure 6. Non-informative vision experiment. Scatter plot of the non-informative vision effect plotted against the average haptic deviation. Each data point represents the non-informative vision effect for a single participant.

Visual Interference Experiment

In the visual interference experiment the within-subject factor of visual interference (-40°, -20°, 0°, 20°, 40° compared to the haptic orientation) and the between-subject factor of gender were analyzed in a repeated measures ANOVA. Note that negative values of the visual interference are away from the expected direction of deviation, and positive values are towards the expected direction of deviation. The percent changes with respect to the non-informative vision experiment as a function of the visual interference are shown in Figure 7. In comparison with veridicality, a positive direction indicates an increase and a negative direction a decrease in the deviations. The main effect of visual interference was significant ($F(1.865,33.571) = 32.929$, $p < .00001$, $\varepsilon = .466$), as was the interaction between visual interference and gender ($F(1.865,33.571) = 9.328$, $p < .001$, $\varepsilon = .466$). On the contrary, the gender factor was not significant ($F(1,18) = .783$, $p = .388$). Pair-wise comparisons showed that all the differences between visual interference levels were significant ($.00001 < p < .05$), except for the comparison between -40° and -20°. Follow-up repeated measures ANOVAs with the same factors, but conducted separately on the male and female groups, revealed a significant main effect of visual interference for both males ($F(1.589,14.3) = 25.689$, $p < .0001$, $\varepsilon = .397$) and females ($F(4,36) = 8.355$, $p < .0001$). Subsequent pair-wise comparisons revealed significant differences between all visual interference levels for the male group (2.498 < *t*(9) < 6.095, .001 < *p* < .005), except for the comparisons between -40° and -20°, 0° and 20°, 0° and 40°, and between 20° and 40° (.766 < *t*(9) < 2.779, *p* > .084). On the contrary, significant differences were found for the female group between visual interference levels of -20° and 20°, and of -20° and 40° (*t*(9) = 3.944, *p* < .05. and *t*(9) = 3.823, *p* < .05, respectively). All other comparisons did not reach significance (1.215 < *t*(9) < 3.353, *p* > .064).

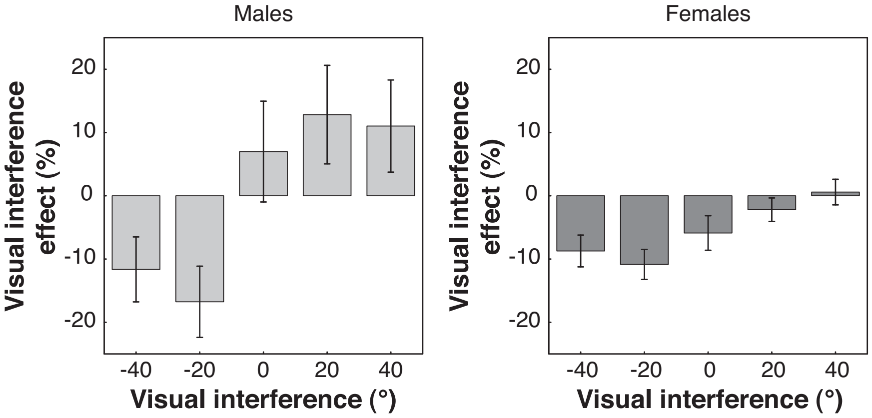

Figure 7. Visual interference experiment. Bar chart of the visual interference effect plotted as a function of the visual interference. The left bar chart presents the male group data and the right bar chart presents the female group data. The error bars indicate the standard error of the mean.

The visual interference effect was further analyzed by linearly regressing the percent changes as a function of the visual interference for each participant individually. The slopes of the regression function were used as estimates of the strength of the visual interference effect. Since the intercepts do not convey any information of interest they were not further analyzed. Simple two-tailed *t*-tests showed that the visual interference strength was significantly different from zero for both the male group (*t*(9) = 5.626, *p* < .0005) and the female group (*t*(9) = 3.542, *p* < .01). Subsequently, we considered the strength of the visual interference effect as a function of the average haptic deviation and gender by conducting a stepwise regression analysis for factor selection. The same criteria as above were used to decide which factors to include and which to exclude. Again the gender factor did not produce a significant improvement of the regression model. On the other hand, the average haptic deviation showed to be a significant predictor of the visual interference effect (*F*(1,18) = 5.785, *p* < .05). The visual interference strength (percent change/degree) could be expressed as:

.77 - .009 * average haptic deviation (*r* = .49).

From this it follows that when the average haptic deviation was larger, the visual interference strength and therefore the visual interference effect became weaker (see Figure 8).

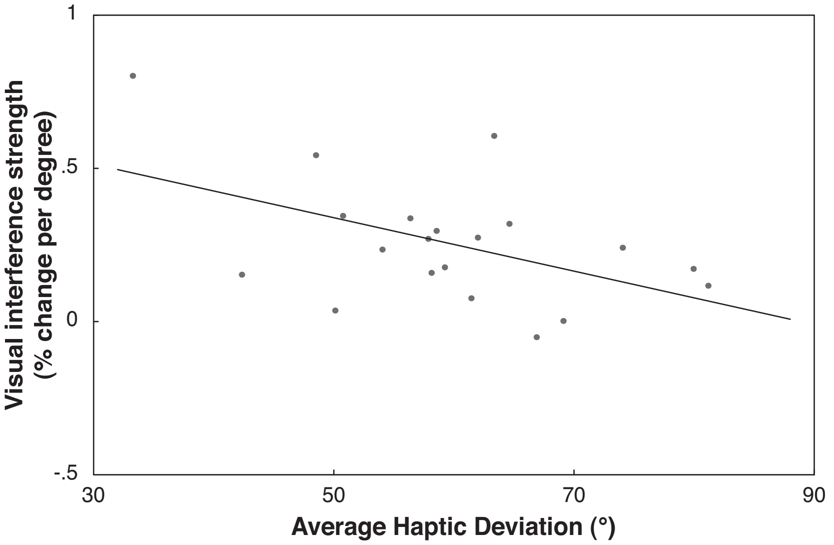

Figure 8. Visual interference experiment. Scatter plot of the visual interference strength (slope of the regression line fitted to the individual visual interference effects as a function of the visual interference) plotted against the average haptic deviation. Each data point represents the visual interference strength for a single participant.

Discussion

In the present study, we addressed the question of how certain aspects of the visual sensory modality interact with haptic spatial processing. We explored the connection between haptic spatial processing and the influence of non-informative vision (i.e., vision of the near space, but without any visual information that is directly relevant to the task). Furthermore, we examined the interfering effect of visual information by simultaneously providing discordant haptic and visual inputs. Our main interest was to tackle the question of whether the occurrence and the strength of the effects of non-informative vision and visual interference are modulated by the inter-participant differences usually present in haptic spatial processing, which are thought to reflect a differential contribution of an egocentric and an allocentric reference frame.

A first comparison between experiments showed that additional sources of visual information had an ameliorating effect on performance. However, this first simplified conclusion does not take into account the differences between the conditions of each experiment, and the expected gender-related and the inter-participant idiosyncrasies. To deepen the understanding of these factors we discuss the three experiments separately.

Our first experiment, the haptic baseline experiment, confirmed the systematic pattern of deviations found in previous studies on the parallelity task. Participants deviated substantially from veridicality showing all the same directional bias: the right bar has to be rotated clockwise with respect to the left bar in order to be perceived as parallel and vice versa. The magnitude of these deviations was observed to be participant-dependent and ranged from 33° to 81°. Although males showed an advantage in performance with respect to females, the distributions of deviations of the two genders were not strictly separated but overlapped, suggesting common underlying processes determining the systematic deviations. The systematic directionality of the deviations provided further strong evidence that the origin of these deviations has to be linked to the biasing influence of the hand orientation. We suggest that the magnitude of the deviations depends on the proportion to which the egocentric and the allocentric frames of reference contribute. This interpretation finds support in all the previous studies on haptic parallel matching (for a review, see Postma et al., 2008). The present results make clear that the distribution of deviations in the population can range as a continuum between the representations of space defined by the allocentric and the egocentric reference frames.

In our second experiment, participants were allowed to see the surrounding environment during the haptic parallelity task. Therefore, visual information was available, but it was non-informative with respect to the demands of the task. Despite this, we observed a beneficial effect of non-informative vision on performance. Possibly, additional information on the position of bars and hands could also originate from proprioception (e.g., from neck muscles) and may contribute to this effect. The direction and the size of the effect were consistent with previous studies. Zuidhoek et al. (2004) reported an improvement of about 9%, whereas Newport et al. (2002), who used a set-up with different characteristics, measured an improvement of about 17%. In our experiment the average improvement due to non-informative vision was 8.7%. Thus, the visual information of the surrounding environment stimulates the use of the allocentric reference frame and consequently reduces the biasing effect of the egocentric reference frame. Interestingly, the difference in performance between genders increased in this experiment. Males improved by 14.7%, whereas females did not significantly change their performance (2.7%). To disentangle a purely gender based difference from a difference that originates in how haptic spatial information is processed, we considered as a further step in the analysis of this effect the magnitude of the non-informative vision effect as a function of the average haptic deviation. The average haptic deviation measured in the haptic baseline experiment was taken as the indicator of the contributions of the reference frames. We found that the average haptic deviation was a significant predictor of the non-informative vision effect. Specifically, the larger the average haptic deviation, the smaller the non-informative vision effect was in the range of interest. In this light, we can suppose that the larger the biasing influence of the egocentric reference frame, the more likely the suppression of the processes that integrate haptic and visual information will be. The reinforcement of the allocentric reference frame was, therefore, less likely to occur. This relation indicates that the preexisting tendency to recode haptic spatial information into a specific reference frame may have a direct influence on the way visual information, when made available, is integrated.

A secondary purpose of the non-informative vision experiment was to explore the relation between orienting mechanisms and hemispace. Zuidhoek et al. (2004) found that orienting the gaze towards the reference bar induced a decrease in the deviations in the haptic parallelity task. The facilitation could be explained by a more accurate perception of the orientation of the reference bar in relation to the left hand, since the reference bar was always placed in the left hemispace. Our experimental design counterbalanced both the gazing direction and the position of the reference bar in either the left or the right hemispace. Neither the gazing direction nor the hemispatial position showed a significant change in performance. The fact that no gazing direction effect was observed could be due to a difference in the experimental design: Zuidhoek et al. (2004) grouped the trials in a blocked design according to the gazing direction, whereas in our experiment the trials were completely randomized. We might speculate that the occurrence of the gazing direction effect is dependent on a prolonged allocation of attention to the position in space where the relevant stimulus is located.

In our third experiment, the visual interference experiment, haptic performance was parametrically varied by the simultaneously presented visual information. When the visual bar was presented in an incongruent orientation with respect to the haptic bar, but in the opposite direction to the haptic systematic deviation, a partial reduction of the haptic systematic deviation was shown. An opposite pattern was observed, but less clearly, when the visual bar was presented in an incongruent orientation with respect to the haptic bar, but in the same direction as the haptic systematic deviation. Interestingly, even in the case when haptic and visual information were congruent, performance could still vary with respect to the non-informative vision experiment. On the basis of the foregoing, it might be hypothesized that an intrinsic misalignment between haptic and visual reference frames could be at the origin of this discrepancy. The general pattern of deviations as a function of the visual interference is in accordance to the effect reported by Kaas et al. (2007). Although the visual input was explicitly defined as irrelevant for the task at hand, we observed a partial integration between modalities that interfered with the execution of the haptic parallelity task.

The visual interference strength estimated from the slope of the fitted regression line was different among participants. The steepness of the slope was more pronounced for the group of male participants. For this reason, as a further step, we explored the visual interference strength as a function of the average haptic deviation. Similarly to the non-informative vision experiment, we found that the average haptic deviation was a significant predictor of the visual interference strength. The lower the average haptic deviation was, the more conspicuous the visual interference strength tended to be, thus indicating an inability to disregard a visual stimulus that is close and similar to the haptic stimulus. On the other hand, participants that showed a stronger hand orientation bias were less likely to be influenced by the simultaneously presented visual information. Therefore, also the way the visual interference effect occurs suggests that the mechanisms underlying haptic spatial processing can exert influence on how the information from the visual modality is processed and integrated.

A generally accepted view is that the brain employs multiple frames of reference to construct spatial representations of the external world (Colby & Duhamel, 1996; Flanders & Soechting, 1995; Gross & Graziano, 1995; Paillard, 1991). For haptic spatial processing we propose that an egocentric and an allocentric reference frame interact in the construction of the representation of space, where the biasing influence of the egocentric reference frame can vary in its magnitude between participants. This interpretation was shown to well describe the inter-participant differences. In addition, we suggest that the specific contributions of the two reference frames can promote or impede the integration of supplemental sources of visual information. Spatial processes specific to the haptic modality may influence the processes that combine haptic and visual information. These results are in support of the existence of strong but flexible cross-modal associations in the construction of spatial representations.

In summary, we showed a beneficial effect of non-informative vision and a biasing effect of interfering visual information on haptic perception of space. Most interestingly, the magnitude of the hand orientation bias was found to be related to both the effects of non-informative vision and visual interference.

Chapter 5

Haptic Mental Rotation Revisited: Multiple Reference Frame Dependence

Abstract

The nature of reference frames involved in haptic spatial processing was addressed my means of a haptic mental rotation task. Participants assessed the parity of two objects located in various spatial locations by exploring them with different hand orientations. The resulting response times were fitted with a triangle wave function. Phase shifts were found to depend on the relation between the hands and the objects, and between the objects and the body. We discarded the possibility that a single reference frame drives spatial processing. Instead, we found evidence of multiple interacting reference frames with the hand-centered reference frame playing the dominant role. We propose that a weighted average of the allocentric, the hand-centered and the body-centered reference frames influences the haptic encoding of spatial information. In addition, we showed that previous results can be reinterpreted within the framework of multiple reference frames. This mechanism has proved to be ubiquitously present in haptic spatial processing.

Volcic, R., Wijntjes, M. W. A., & Kappers, A. M. L. (submitted). Haptic mental rotation revisited: multiple reference frame dependence.

Introduction

Any spatial characteristic of an object can only be defined relative to some reference frame, but there are in fact multiple reference frames through which the human system is able to encode objects. For instance, visual information of an object is acquired in retinocentric coordinates, but it can be also encoded in head-centered coordinates to stabilize perception during eye movements, or in body-centered coordinates to allow the perceiver to act on that object. The object can also be encoded relative to the environment in an allocentric reference frame. Similarly, haptic information is usually gathered via the hand, the primary sense organ for touch. The spatial information in hand-centered coordinates is then transposed to hierarchically higher reference frames to fulfill the needs of an active human system. In general, the perceiver's behavior based on both visual and haptic spatial information is assumed to be a result of processes that combine the different frames of reference within each modality as well as between modalities.

Whenever we touch an object we establish a relation between the perceiving hand and the object and consequently the orientation of the object with respect to the hand can be obtained from this relation. To extract the spatial characteristics of the object in the environment (i.e., its orientation and its location) additional relations have to be established also between the perceiving hand and the perceiver, and between the perceiver and the surrounding environment. From this point of view, it can be hypothesized that multiple encodings of the same object coexist simultaneously. For instance, Oldfield and Philips (1983) proposed that haptic perception of an object involves both an egocentric and an allocentric frame of reference and that it is the relative position of the egocentric reference frame within the allocentric reference frame that determines the perceptual experience. Similar conclusions were reached also in studies where the task was to identify letters or numbers traced on surfaces of the perceiver's body when the relative spatial orientations and positions of the body surfaces and of the stimuli varied (Corcoran, 1977; Duke, 1966; Krech & Crutchfield, 1958; Natsoulas & Dubanoski, 1964; Parsons & Shimojo, 1987).

The role of reference frames in haptic perception was highlighted in a series of studies investigating the spatial relations between objects (Kappers, 1999; Kappers & Koenderink, 1999; for a review, see Postma et al., 2008). Systematic deviations were observed in the task where blindfolded participants were asked to align two objects in such a way that they felt parallel to each other. The two objects had to diverge away from the body, on average by about 50°, to be perceived as parallel. A biasing effect of the hand orientation was pinpointed as the dominant factor (Kappers, 2004; Kappers, 2005; Kappers & Viergever, 2006; Volcic et al., 2007). As a further step, an interaction between the hand-centered egocentric reference frame and the allocentric reference frame was presupposed and subsequently the deviations were successfully described both in two-and in three-dimensions with a weighted average model that balances the contributions of the two reference frames (Kappers, 2007; Volcic & Kappers, 2008). These studies have shown the primary role of the hand-centered egocentric reference frame in the encoding of information about objects and how influential this encoding can be in haptic spatial processing.

The interplay of reference frames has also been demonstrated in mental rotation tasks. In vision, for example, different studies have attempted to discover which reference frame is used in a mental rotation task by disassociating the retinal upright from the gravitational upright by having participants tilt their heads in certain conditions (Corballis et al., 1976, 1978). Response times are generally fastest when stimuli are perfectly aligned with the perceptual reference frame. In addition, the degree of misalignment between the orientation of the stimulus and the orientation of the frame produces a linear increase in response time. On the basis of these premises, it is possible to derive in which perceptual reference frame the stimuli are actually encoded. For instance, when the head is tilted, stimuli in gravitational upright orientation are responded to most quickly and response times increase as a function of the misalignment from this orientation. This pattern of response times is consistent with the use of an allocentric, gravitationally aligned, reference frame. On the other hand, a pattern of response times shifted to match the retinally upright orientation is consistent with the use of an egocentric, retinally aligned, reference frame. Corballis et al. (1976, 1978) showed that stimuli tend to be encoded in a reference frame midway between the egocentric and the allocentric reference frame, where the latter one is more dominant. McMullen and Jolicoeur (1992) reached similar conclusions.

In a similar fashion, the mental rotation task has been employed to identify the reference frame in which objects are haptically encoded. Carpenter and Eisenberg (1978) presented a single letter haptically in a normal or mirror-image form in various orientations. Participants had to retrieve from memory the letter in its canonical orientation and compare it with the presented letter to decide whether the letter was normal or a mirror image. One of the purposes of their study was to investigate the influence of hand position. In two conditions they varied the orientation of the hand relative to the participant's body while keeping the stimulus in the same location. In the first condition the right hand was parallel to the participant's midsagittal plane, whereas in the second condition the right hand was rotated counterclockwise by 60°. The influence of hand position was evident from the patterns of the response time functions that differed in their phase shift. In both conditions the fastest response time was observed when the hand was aligned with the stimulus, and response times increased with larger differences in orientation between the stimulus and the hand. This means that whereas in the first condition the fastest response time was measured when the major axis of the stimulus was parallel to the participant's midsagittal plane, in the second condition the stimulus had to be rotated by approximately 60°. On the basis of these results, Carpenter and Eisenberg (1978) concluded that the orientation of a letter is encoded with respect to a hand-centered reference frame.

A more recent study on haptic mental rotation led Prather and Sathian (2002) to different conclusions. They applied an embossed letter on the participant's finger pad and, as in Carpenter and Eisenberg (1978), participants had to determine if the letter was normal or a mirror image. In one condition the finger pad was positioned horizontally in front of the participant, centered in the midsagittal plane and parallel to it, whereas in the second condition the finger pad was also centered in the midsagittal plane but orthogonal to it. Despite the change in the orientation of the finger pad and, consequently, in the orientation of the hand, the response time functions in the two conditions were very similar. Prather and Sathian (2002) concluded that haptic stimuli are not encoded in a hand-centered reference frame and suggested that the encoding might occur in a body-, head- or eye-centered reference frame. In addition, they supposed that the phase shift in the direction of the hand orientation found by Carpenter and Eisenberg (1978) could be accounted for by a head-centered reference frame if participants kept their head in alignment with their hand.

The main aim of this paper was to experimentally disentangle the different reference frames that may play a role in haptic mental rotation and, generally, in haptic spatial processing. To pursue this purpose we used a bimanual mental rotation task that requires participants to determine whether two objects of the same shape and in different orientations felt by the two hands are mirror images of each other or identical except for orientation. This task is also known as the handedness recognition task. In this way, objects can be directly compared with each other in contrast to the comparison between the stimulus and its memory-based representation as was the case in all the earlier studies on haptic mental rotation. We restricted our quest to a group of reference frames that are most likely involved in haptic spatial processing: the allocentric, the hand-centered egocentric and the body-centered egocentric reference frames. In the allocentric reference frame objects are represented relative to the environment that is extrinsic to the perceiver. In the hand-centered egocentric reference frame objects are represented relative to the perceiver's hand, and, finally, in the body-centered egocentric reference frame objects are represented relative to the perceiver's body. Our definition of the latter reference frame comprises also a head-centered reference frame as long as the head faces forward. To dissociate the influences of the different reference frames we devised different experimental conditions in which the two objects to compare were explored with different hand orientations and were located in different positions relative to the perceiver's body (see Figure 1, left panel). We expected that the employment of the relevant reference frame would evince itself in a specific phase shift of the response time function. In the simplest case, if only an allocentric reference played a role, the quickest response time should be observed when the two objects are physically aligned. Response times would linearly increase, both in the positive and in the negative direction, as a function of an increase in the orientation difference between the two objects. This pattern, i.e., a response time function with no phase shift, would be independent of the experimental condition and it is exemplified in the leftmost column of Figure 1 (right panel). This is essentially similar to the Shepard and Metzler (1971) model. They used a linear function to model response times. The triangle wave function is the generalized version of this function taking into account the periodicity. Predictions that are dependent on the experimental condition could be made for the cases in which either the hand-centered or the body-centered reference frame would play a role in haptic mental rotation. The response time function was expected to shift horizontally (phase shift) depending on the positions of the hands or on the position of the objects with respect to the body (see center and rightmost columns in Figure 1, right panel). For example, if the body-centered reference frame is used, the parity of objects oriented similarly with respect to the radial direction of the body-midline should be identified fastest. The direction and the magnitude of these phase shifts would therefore indicate the perceptual reference frame in which the objects are encoded. These predictions were based on a selective process, in which only one reference frame is selected and guides haptic spatial processing without any influence from other reference frames. Contrary to this view, recent studies mentioned earlier have shown that haptic perception of spatial relations is based on a combination of multiple frames of reference. In line with this interpretation we expected interacting reference frames also in haptic mental rotation. As a corollary, any phase shift intermediate to the predictions made on the basis of the selective process would suggest a mechanism that combines the different reference frames. In this case we expected each reference frame to contribute to haptic spatial processing according to a specific weight.

Materials and Methods

Participants

Six male participants took part in this experiment. Participants M.W. and R.V. are authors of the paper. All the others were undergraduate students and were remunerated for their efforts. Participants had normal haptic, somatosensory and motor functioning. None of the participants (except the authors) had any prior knowledge of the experimental design and the task.

Apparatus and Stimuli

The set-up consisted of a table (150 × 75 × 75 cm) on which two iron plates (30 × 30 cm) could be positioned, one on either side of the participant’s midsagittal plane. The iron plates were covered with a plastic layer on which a protractor with a radius of 10 cm was printed. The centers of the two protractors were either 30 or 120 cm apart and 15 cm from the long table edge. The participants were seated on a stool in a fixed position in front of the table. Their body midline was 15 cm from the edge of the table. The participant's head was facing forward during experimental sessions. An aluminum object, with an axle in the middle, was inserted in the center of each protractor and could be rotated freely by the experimenter. The objects used as stimuli were made of two cylindrical bars, with a diameter of 1 cm. The main bar had a length of 20 cm, and attached to this at 5 cm from the centre was a smaller bar with a length of 5 cm. One pair of objects had the smaller bar attached on the right side of the main bar, whereas the other pair had it attached on the left side. The main bar had an arrow-shaped end on one side that allowed the orientation to be read off with an accuracy of 0.5°. Small magnets were attached under the bar to prevent accidental rotations.

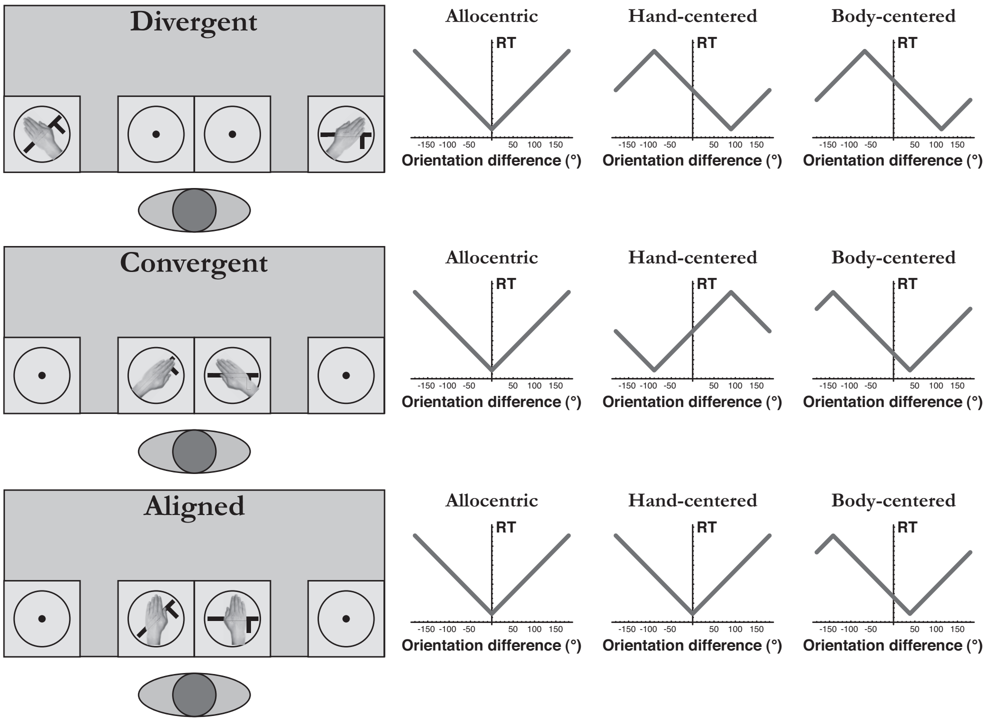

Figure 1. Experimental conditions (left panel) and predictions of the response time (RT) function for each condition according to the allocentric, the hand-centered and the body-centered reference frame (right panel). Participants could freely explore the objects during the experiment with the only constraint being the orientation of the hands determined by the condition.

The objects were connected to electrical wires which were plugged into the touch sensitive contact of the custom build stand-alone response time measuring device. The moment the hands touched the stimuli the contact was registered through a touch sensitive contact and response time measurement started. Inside the device, a 50 Hz electrical field was generated. When the objects were touched the impedance change caused a drop in the field frequency. If this change reached a certain threshold the time measurement started. Time measurement terminated with a vocal response registered through a headset microphone that was also attached to the measuring device. The response time was then fed into a computer, where it was stored. The software that communicated with the device was written in LabView™.

Stimuli were presented in pairs. The stimulus on the left side of the participant's midsagittal plane was oriented at 45°, 135°, 225°, or 315°. The 0° orientation was aligned along the left–right axis of the table and an increase in degrees signifies a rotation in the counterclockwise direction. The stimulus on the right side was rotated with respect to the left stimulus for a number of degrees between -170° and 170° in steps of 20°. Each stimulus was paired with either another identical stimulus (Same trial) or its mirror version (Different trial). The stimuli were presented in three different experimental conditions. In the Divergent condition the two stimuli were located 120 cm apart and when touching them the two hands were diverging by approximately 90° (see Figure 1, left panel, top). In the Convergent condition the two stimuli were 30 cm apart and when touching them the two hands were converging by approximately 90° (see Figure 1, left panel, middle). In the Aligned condition the stimuli were again 30 cm apart and the two hands were aligned with each other (see Figure 1, left panel, bottom). In total, each participant completed 864 trials (2 objects × 4 orientations of the left located object × 18 orientations of the right located object × 2 same/different pairs × 3 conditions). The order of trials in each experimental condition was random and different for each participant. The order of the experimental conditions was counterbalanced across participants.

Procedure

Participants had to perform a haptic mental rotation task. The experimenter set two stimuli in their locations and gave a start signal to the participant. The blindfolded participants were instructed to touch the two objects simultaneously with their hands oriented in the way predefined by the condition. They had to respond as fast as possible whether the two stimuli were the same or different. It was also emphasized that the answer should be correct. Participants received feedback on whether their answer was correct. When an incorrect response was given, the trial was repeated at the end of the experimental condition so that in the end a full set of correct trials was measured. The response time measurement initiated when the participant first touched the stimuli and terminated when the participant verbally responded either "same" or "different".

The experimental conditions were preceded by practice trials until the participant was confident with the execution of the task. For none of the participants did the training session exceed 80 trials. The word "rotation" was not used in the instructions.

The experimental sessions ended after one hour to prevent fatigue of the participants and were performed on separate days. They took on average 8 h to complete all conditions.

Data Analysis

The error rates in all the experimental conditions were low (below 5%) and were not further analyzed. Data analysis of the response times was limited to the Same trials, because the Different trials do not convey any information since the angle through which Different objects must be rotated to achieve congruence is not defined.

Fitting Procedure

The individual response times of the Same trials were grouped for each condition and orientation difference. Since the response times are usually not normally distributed, we took for each orientation difference the median response time of the grouped data. These medians were then used to fit a triangle wave function through the data of each participant (see Figure 2). The triangle wave function is a periodic function with a fixed wave period of 360° and is expressed as:

$$T\left(x, A, \phi, \mu\right) = 2A\left|\mathrm{Int}\left(\frac{x-\phi}{360^\circ}\right) - \frac{x-\phi}{360^\circ}\right| + \mu - \frac{A}{2}, \tag{1}$$

where A is the amplitude, ϕ is the phase shift and μ is the vertical shift. The function Int(x) gives the integer closest to x. For $\phi = 0$, the function is essentially identical to the function used by Shepard and Metzler (1971). Note that the triangle wave function is not continuously differentiable and can thus not describe a physical phenomenon. This issue, though, is of minor concern for the purposes of this study.

Estimation of the Weighting Factors

We suppose that the phase shift of the response time function is determined by a weighted contribution of an allocentric reference frame, a hand-centered egocentric reference frame and a body-centered egocentric reference frame. Therefore, the phase shift of the response time function can be expressed by the following equation:

$$\phi = \left(1 - w_1 - w_2\right)\phi_{\mathrm{Allo}} + w_1\phi_{\mathrm{Hand}} + w_2\phi_{\mathrm{Body}} \qquad (0 \le w_1 \le 1, 0 \le w_2 \le 1), \tag{2}$$

where ϕ_{Allo}, ϕ_{Hand} and ϕ_{Body} correspond, respectively, to the phase shifts that would be expected if only an allocentric, a hand-centered egocentric or a body-centered egocentric reference frame were used in a specific condition. These values are fixed and are defined on the basis of the position of the participant with respect to the set-up. The size of the weighting factors (w_1, w_2) modulates the relative contributions of the three reference frames. The weighting factors are the parameters used in the fitting procedure.

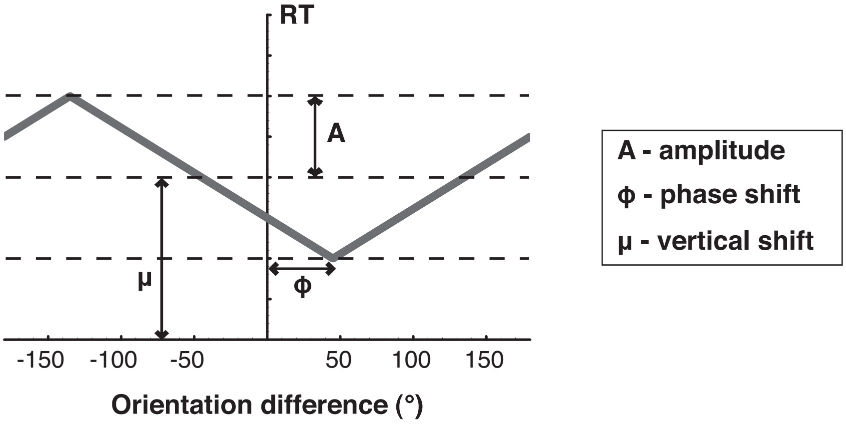

Figure 2. Triangle wave function used to fit the response times as a function of the orientation difference between the two objects. The function is defined by three parameters: amplitude (A), phase shift (ϕ) and vertical shift (μ). RT is response time.

The above equation can be applied to each of the three experimental conditions of our study. Since we assume that the weighting factors are independent from the location in space, our intent was to compute weighting factors that could capture the phase shifts of all three conditions. Hence, to estimate the weighting factors, that is, the contributions of the different reference frames, we defined this set of equations:

$$\begin{cases} \phi_{\text{Div}} = \left(1 - w_1 - w_2\right)\phi_{\text{Allo\_Div}} + w_1\phi_{\text{Hand\_Div}} + w_2\phi_{\text{Body\_Div}} \\ \phi_{\text{Conv}} = \left(1 - w_1 - w_2\right)\phi_{\text{Allo\_Conv}} + w_1\phi_{\text{Hand\_Conv}} + w_2\phi_{\text{Body\_Conv}} \\ \phi_{\text{Alig}} = \left(1 - w_1 - w_2\right)\phi_{\text{Allo\_Alig}} + w_1\phi_{\text{Hand\_Alig}} + w_2\phi_{\text{Body\_Alig}} \end{cases} \tag{3}$$

and extracted the weighting factors through a least-square error minimization procedure. The estimation of the weighting factors was performed individually per participant, because participant-dependent differences in the weights might be expected. The terms ϕ_{Div}, ϕ_{Conv} and ϕ_{Alig} correspond, respectively, to the phase shifts measured in the three experimental conditions. All the other ϕ terms correspond to the predicted phase shifts that depend on the experimental condition and are represented in Figure 1 (right panel). The predicted phase shifts were calculated on the basis of the position and orientation of the objects with respect to the orientations of the hands for the hand-centered reference frame predictions, and with respect to the body midline for the body-centered reference frame predictions. For instance, two objects are defined as having the same orientation within a certain reference frame when they are identically oriented with respect to either the hand or to imaginary lines irradiating from the participant's body midline. The predictions for the allocentric reference frame are independent of the position of the objects with respect to each other or with respect to the participant and are therefore constant.

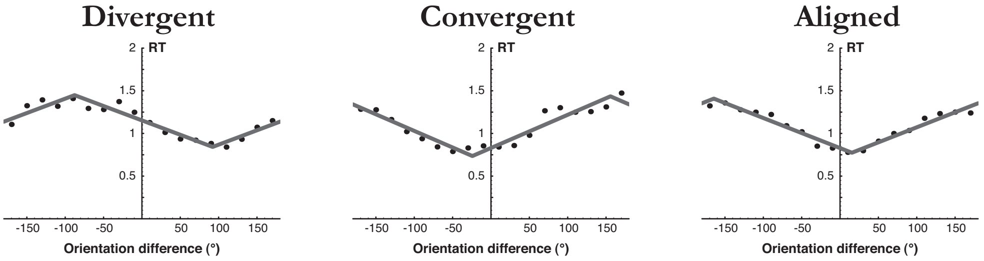

Figure 3. Response times as a function of the orientation difference averaged over all participants for the Divergent, Convergent and Aligned conditions. Data are fitted by the triangle wave function.

Results

The graphs in Figure 3 show the response times as a function of the orientation difference between the two objects averaged over all participants in the Divergent, Convergent and Aligned conditions. The triangle wave function was fitted through the data. Several observations can be made already at first sight. First of all, the phase shift of the fitted function relative to the physical alignment varies in the different conditions and can largely deviate from zero. This indicates that the lowest response times were measured when the two objects actually had a different orientation and were not physically aligned with each other. Second, from the point defined by the phase shift the response times showed a positive linear relationship with respect to smaller and larger orientation differences supporting the adoption of the triangle wave function as the fitting function. The explained variance was between 89% and 94%.

In the Divergent, Convergent and Aligned conditions the phase shifts of the response time function were 92.2°, -24.2°, and 15.4°, respectively. Note that the direction of the phase shifts corresponds with the relative orientations of the two hands touching the objects. For instance, in the Divergent condition the lowest response times were measured when the two objects were approximately orthogonal to each other, but actually had very similar orientations with respect to the left and right hands. In the Convergent condition the direction was in agreement with the relative orientation of the hands, although the magnitude of the phase shift was reduced. The phase shift in the Aligned condition was still positive, but close to the actual physical alignment of the objects.

Condition	Participant	A (s)	ϕ (°)	μ (s)	R^2
Divergent	M.W.	0.87	90.3	1.13	.89
	R.V.	0.48	94.5	0.96	.57
	B.K.	0.68	85.1	1.22	.70
	D.B.	0.40	92.9	1.05	.67
	O.D.	0.94	97.3	1.53	.63
	K.B.	0.28	88.9	0.98	.44
Convergent	M.W.	0.91	-40.6	1.05	.86
	R.V.	0.62	-16.4	0.92	.89
	B.K.	1.35	-39.3	1.48	.69
	D.B.	0.26	-64.2	1.01	.51
	O.D.	0.99	4.4	1.24	.82
	K.B.	0.33	-23.4	0.81	.55
Aligned	M.W.	0.63	9.2	0.91	.85
	R.V.	0.71	4.4	0.93	.81
	B.K.	0.73	16.6	1.08	.65
	D.B.	0.50	9.6	1.19	.43
	O.D.	0.98	23.6	1.56	.74
	K.B.	0.26	19.1	0.88	.57

Table 1. For every participant and every condition, their amplitude (A), phase shift (ϕ), vertical shift (μ) and R^2 of the triangle wave function fits.

To further analyze the response time measurements we looked at the data of the individual participants. Table 1 charts the parameters of the fitting function for each condition and each participant. In addition, the R^2 of each fit are listed in the rightmost column showing good fits for all participants and conditions. Three repeated measures ANOVAs were performed on the amplitude (A), on the phase shift (ϕ) and the vertical shift (μ) with the experimental conditions as a factor. Both the amplitudes and the vertical shifts were not significantly different among the three experimental conditions. Therefore, the average response time and the range of the response times were stable in all the conditions. Consequently, also the speed of rotation (180°/2A) was fairly invariable: 175.8°/s, 168.5°/s, and 167.6°/s, in the Divergent, Convergent and Aligned conditions, respectively. On the other hand, the repeated measures ANOVA on the phase shifts revealed a significant effect of condition ($F(2,10) = 137.745, p < .0001$). Subsequent pair-wise comparisons with Bonferroni corrections showed significant differences between the Divergent and Convergent conditions ($p < .0001$), between the Divergent and Aligned conditions ($p < .0001$), and between the Convergent and Aligned conditions ($p < .05$). The phase shifts of each participant are represented in the bar chart of Figure 4. The phase shifts agree quite well across participants.

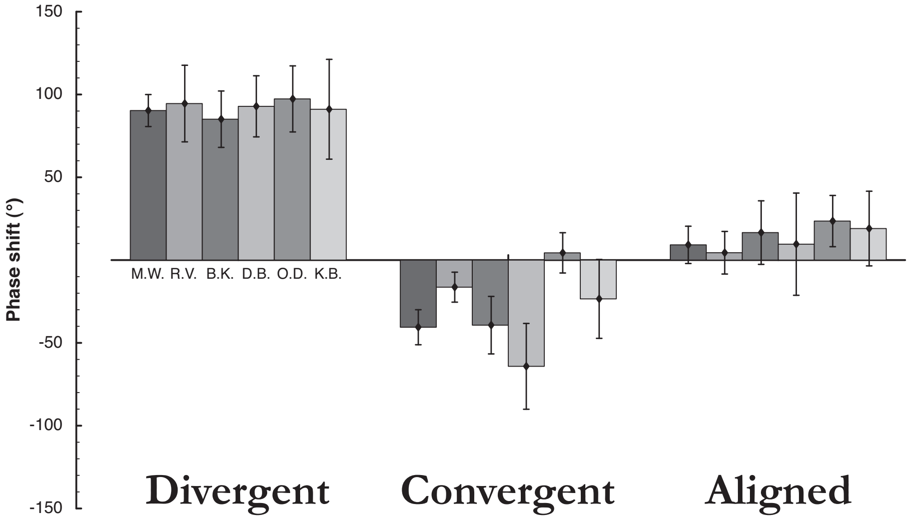

Figure 4. Phase shifts (ϕ) of each participant in the Divergent, Convergent and Aligned conditions. Error bars indicate the 95% confidence interval of the standard error of the mean as obtained from the triangle wave function fits.

The phase shifts do not match perfectly with any of the predicted phase shifts (see Figure 1, right panel). The use of an allocentric reference frame does not predict any phase shift. The use of a hand-centered egocentric reference frame predicts a larger negative phase shift in the Convergent condition. And, finally, the use of a body-centered egocentric reference frame predicts a positive phase shift in the Convergent condition. Our next step was therefore to investigate if the measured phase shifts can be explained by a combination of the three reference frames. The question was if a combination of weighting factors exists that integrates the contributions of the reference frames in such a way as to be consonant with the measured phase shifts. The error minimization procedure explained in the Methods section was applied to estimate the weighting factors for each participant separately. The resulting weights are shown in Figure 5. It is evident that the hand-centered egocentric reference frame plays the primary role. The body-centered egocentric reference frame appeared to be the second most influential reference frame; finally, the allocentric reference frame was only minimally involved. On average the weights were .12, .62, and .26 for the allocentric, the hand-centered egocentric and the body-centered egocentric reference frame. In addition, it is interesting to observe that since the contribution of the allocentric reference frame is uniform across participants (*SD* = .049), participants differ among each other only with respect to the contributions of the hand- and body-centered reference frames (*SD* = .142 and *SD* = .103, respectively).

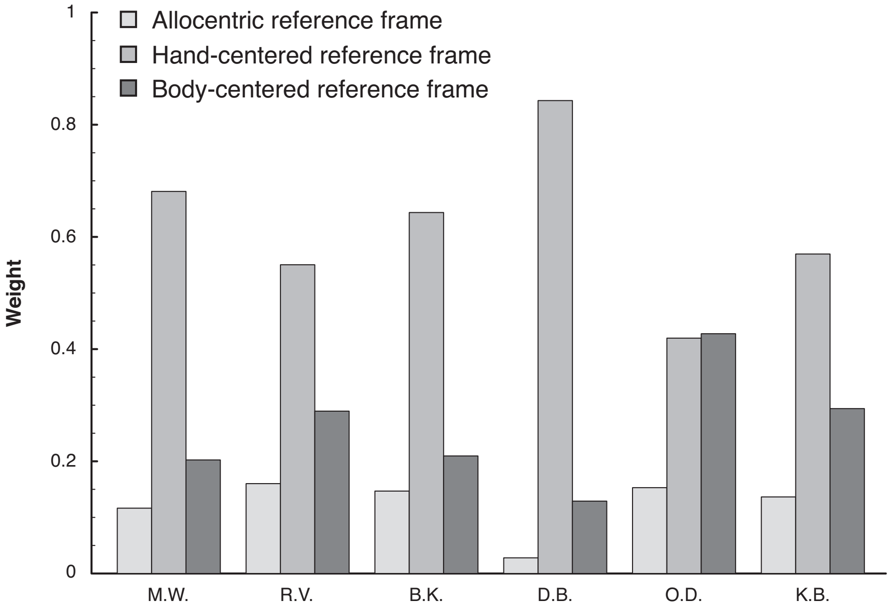

Figure 5. Estimated weights of the allocentric, the hand-centered and the body-centered reference frame for each participant.

Discussion

In the present study, we investigated the role that reference frames play in haptic spatial processing. In a bimanual haptic mental rotation task participants had to compare the parity of two objects located in different spatial locations by exploring them with different hand positions. Our goal was to dissociate the influence of the allocentric, the hand-centered egocentric and the body-centered egocentric reference frames. The idea that only one of these reference frames is selected and drives haptic spatial processing was rejected. Instead, our data support a dependence on a combination of multiple reference frames, in which the hand-centered reference frame plays the central role.

The influence of a specific reference frame was expected to act on the phase shift of the response time function. If a single reference frame among the allocentric, the hand-centered and the body-centered reference frames had been involved, we would observe the phase shifts represented in Figure 1 (right panel). In fact, the patterns of the response time function were different. The phase shift was modulated by the diverse hand postures and positions of the objects with respect to the perceiver. However, the causing factor cannot be attributed to the influence of a single reference frame. A dominant role of the allocentric reference frame was excluded merely on the fact that phase shifts were observed. A prevailing role of the body-centered reference frame was also excluded, since it could have never predicted a negative phase shift in the Convergent condition. On the other hand, Hand-centered reference frame predictions were successful in capturing the directionality of the shifting response time function, although also in this case the observed phase shift diverged from the predicted ones. On the basis of these observations we discarded any explanation that involves an exclusive use of a particular reference frame, in contrast to Carpenter and Eisenberg (1978) and Prather and Sathian (2002). Rather, we interpreted the phase shifts of the response time function as a product of the interplay of the allocentric, the hand-centered and the body-centered reference frame. Each of these reference frames actively contributed to the processing of spatial information, but each of them to a different extent, which was estimated by computing the weighting factors. The hand-centered reference frame predominated as the most influencing factor, with the body-centered reference frame placed second, and the allocentric reference frame showing the smallest contribution. This combination of reference frames with their specific weights could actually account for the directions and the extents of the phase shifts in our experimental conditions. None of these reference frames could be excluded without noticeably affecting the accuracy.

In the previous studies on haptic mental rotation, it was suggested that a predominant hand-centered reference frame accounted for the results of Carpenter and Eisenberg (1978), but not for the results of Prather and Sathian (2002). In order to fairly compare past and present results, we extracted the response time data from the above mentioned studies and fitted the triangle wave function to estimate the phase shifts. In Carpenter and Eisenberg (1978), we found a phase shift of 48° in the direction of the hand-centered reference frame; in Prather and Sathian (2002), we found a phase shift of 29°. In the first study, a 60° phase shift would support the view of a complete hand reference frame dominance, whereas in the second study, the phase shift should have been of 90°. The prediction for the body-centered reference frame in Carpenter's study could not be clearly defined, since the exact location of the stimulus with respect to the body is not known. In Prather's study, on the other hand, the body-centered reference frame does not predict any phase shift. Importantly, we confirmed the role of the hand-centered reference frame in Carpenter and Eisenberg (1978), but we also found evidence of the influence of the hand-centered reference frame in Prather and Sathian (2002). This evidence contrasts with their conclusions, which excluded any role of this reference frame. Therefore, we propose that these previous results should be reinterpreted in the framework of multiple interacting reference frames. The differences in the contributions of each reference frame with respect to our results might be due to some fundamental methodological differences, such as the use of alphanumeric characters with their intrinsic canonical orientation, the size of the explored stimuli, and the active versus passive exploration mode.

Since the use of multiple reference frames is in agreement with previous findings on the mechanisms that govern haptic spatial processing, it is of interest to address this subject thoroughly. As we mentioned in the Introduction, multiple reference frames in haptics have been investigated with a task in which participants were required to orient an object to perceive it as parallel to another one. The common outcome was that the systematic deviations from parallelity were biased in the direction of the hand-centered reference frame (Kappers, 2007; Volcic & Kappers, 2008). A minor influence of the body-centered reference frame was also shown in Kappers and Viergever (2006), where deviations from veridicality were observed also in the condition in which the two hands were aligned. In general, the predominant biasing effect of the hand could differ across participants, but more importantly, it was modulated by the specific task demands. For instance, providing non-informative visual information (i.e., vision of the task workspace, but without any visual input that was directly relevant to the task) diminished the biasing influence of the hand-centered reference frame (Newport et al., 2002; Volcic et al., in press; Zuidhoek et al., 2004). The visual information about the surrounding environment seemed to facilitate the contribution of the allocentric reference frame. Similarly, presenting participants with a 10-s delay between the perception of the first object and the parallel setting of the second object led to a decrease of the biasing effect (Zuidhoek et al., 2003). This improvement was interpreted as reflecting a shift from an egocentric towards a more allocentric spatial representation over delay time, similar to findings of several visuo-motor studies (Bridgeman et al., 1997; Carrozzo et al., 2002; Milner et al., 1999; Rossetti, et al., 1996). These observations suggested a sort of continuum between allocentric and egocentric representations in spatial encoding, in which the available information and the task demands induce a certain ratio between the contributions of the different reference frames. In the basic case, the weight of the biasing effect of the hand-centered reference frame was estimated to be approximately .25 on average (Kappers, 2007). The biasing effect was then reduced by additional non-informative visual information or additional processing due to temporal delay. On the other hand, in the present study the weight of the hand-centered reference frame was estimated to be .62 on average. A fundamental question thus emerges: why is there such a substantial difference in the magnitude of the hand-centered reference frame contribution between the previous and the present studies? First of all, whereas the solution of the parallelity task is based on an allocentric description, in the mental rotation task the use of an allocentric reference frame is not necessary per se. The concept of parallelity is implicitly defined with respect to an allocentric reference frame. Therefore, the perceiver is at least forced to strive to encode the spatial information in this reference frame. On the contrary, in the mental rotation task, the perceiver has the freedom to choose among reference frames. Second, the two tasks largely differ in their imposed temporal constraints: in the parallelity task participants took several seconds to set the object to be perceptually parallel, whereas in the mental rotation task the average response time was about one second. We could speculate that as time progresses, haptic spatial processing is less influenced by egocentric references frames and more by the allocentric one. Initially, spatial encoding might be exclusively hand-centered, then progressively more body-centered, and finally allocentric. This hypothetical temporal evolution of reference frames actually fits with the observation that the fastest participant was the one with the highest contribution of the hand-centered reference frame, and the slowest participant was the one with the highest contribution of the body-centered reference frame. For more concrete evidence, though, a much larger sample of participants is needed.

Importantly, the framework of multiple interacting reference frames is not limited to haptic spatial processing, but it is considered to be a general principle in the way the brain transforms, combines and compares spatial representations (Carrozzo & Lacquaniti, 1994; Carrozzo et al., 2002; Cohen & Andersen, 2002; Pouget & Sejnowski, 1997; Salinas & Thier, 2000; Soechting & Flanders, 1992, 1993). Increasing evidence suggests that spatial information can be simultaneously available in different reference frames and the appropriate information may be read out according to ongoing task requirements. The origin of this information can be thus visual, sensorimotor, haptic or auditory and it can be coded in several reference frames, within or between modalities, which have to be combined to achieve the goals of an active perceiver.

In conclusion, we showed that in haptic mental rotation the phase shifts of the response time function are influenced by a specific integration of reference frames and are not dependent on the exclusive use of a single frame of reference. The allocentric, the hand-centered and the body-centered reference frames are the most likely reference frames involved in haptic spatial processing. Among them, the hand-centered reference frame proved to be the most influential. Our results are in agreement with accumulating evidence suggesting that the combination of multiple reference frames is a mechanism governing not only haptic spatial processing, but spatial processing in general.

Chapter 6

The Eyes Touch What the Hand Sees: Amalgamating Modality-Specific Reference Frames

Abstract

The simple experience of a coherent percept while looking and touching an object conceals an intriguing issue: different senses encode and compare information in different modality-specific reference frames. We addressed this problem in a cross-modal visuo-haptic mental rotation task. Two objects in various orientations were presented at the same spatial location, one visually and one haptically. Participants had to identify the objects as same or different. The relative angle between viewing direction and hand orientation was manipulated (Aligned vs. Orthogonal). In an additional condition (Delay), a temporal delay was introduced between haptic and visual explorations while the viewing direction and the hand orientation were orthogonal to each other. Whereas the phase shift of the response time function was close to 0° in the Aligned condition, in the Orthogonal condition we observed a consistent phase shift in the hand's direction. In the Delay condition we found a phase shift intermediate to the Aligned and Orthogonal conditions. Counterintuitively, these results mean that visuo-haptically misaligned objects were identified quicker. Conforming to our previous findings, the results suggest that the information about an object is acquired in separate visual and hand-centered reference frames which directly influence each other and which combine in a time-dependent manner.

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Introduction

Objects can be recognized and identified using any of our sensory modalities. Since we explore the environment using a variety of modalities, our internal representation of the sensory world is formed by integrating information from different sources. When we, for instance, handle an object the different visual and haptic sources of information converge to form a coherent percept. However, the integration of multisensory information is a challenging problem. First, sensory modalities can vary in their reliability. The extent to which a certain modality influences the final percept depends on the reliability of that modality. Second, each sensory modality encodes the same properties of an object in a different format. Sensory information is encoded in different reference frames and to be integrated they need to be compared. For instance, visual stimuli are initially encoded with respect to the retina, haptic stimuli with respect to the skin of the exploring hand, and auditory stimuli with respect to the head. Therefore, a change in body posture will result in a change in the relation between visual, haptic and auditory encodings of the same object. To compare these different encodings, the actual posture must be taken into account. The present study focuses on this latter issue, that is, on the comparison of spatial information about objects encoded in visual and haptic reference frames.

A simple way to encode the position of an object is to specify its location with respect to a reference frame. For instance, the position of a viewed object can be specified with respect to the eye, and the position of a touched object can be specified with respect to the hand. Similarly, the orientation of objects is also encoded with respect to the same reference frames. Note that in vision the position and orientation of objects can be defined in several reference frames: an eye-centered, a head-centered, an environment-centered, to name a few. For clarity, from here on we will refer to visual reference frames generically. Similarly, several reference frames can be also distinguished in haptics. However, the hand-centered reference frame was identified as being the dominant one (Kappers, 2007; Volcic & Kappers, 2008). To our knowledge, the comparison of spatial information derived from different sensory modalities has been limited to positional information (e.g., Avillac et al., 2005; Cohen & Andersen, 2002; Colby & Duhamel, 1996; Graziano, 2001; Pouget et al., 2002; Pouget & Snyder, 2000); the issue of how orientational information is compared was not addressed yet. However, there is general understanding that objects are encoded in multiple reference frames. Whether a common supramodal reference frame exists in which spatial information is compared or whether reference frames from different sensory modalities directly influence each other, is still an open question though.

How spatial information is encoded and which reference frames are relevant for this encoding was studied behaviorally with, among other methods, the mental rotation task. In this task participants are required to assess as fast as possible whether two objects in different orientations are mirror images of each other or identical except for orientation. In a unimodal haptic mental rotation task it has been shown that, not surprisingly, response times in judging the objects' parity were fastest when the two objects were approximately physically aligned. Response times increased linearly as a function of the objects' misalignment. However, by also changing the hands' orientations with respect to the objects the fastest response times were not observed anymore when the objects were physically aligned, but, on the contrary, when they were approximately aligned with the hands exploring them. The response time function thus shifted in accordance to the relative orientations of the hands. From the phase shift of the response time function it was possible to infer in which perceptual reference frame the objects had been actually encoded. A dominant role of the hand-centered reference frame was found in haptic mental rotation (Carpenter & Eisenberg, 1978; Volcic et al., submitted). Similarly, the influence of reference frames was studied in vision with a variation of this task. Participants had to make a comparison between a presented alphanumeric character and its internal representation. Here, the response time function has been shown to shift in accordance to the participants' head tilt (Corballis et al., 1976, 1978). In this context, fundamental questions arise. Namely, how is spatial information about objects compared across the visual and haptic modalities? And, does one modality take over from the other and by this provide a unique reference frame in which both visual and haptic information are compared? Or, alternatively, do the spatial encodings from the visual and haptic modalities directly influence each other?

To address these problems we used a visuo-haptic cross-modal mental rotation task. One of the objects was viewed and the other was haptically explored. Moreover, we designed the set-up such that both objects were perceptually located in exactly the same spatial position (see Figure 1). The logic behind the present experiment was simple: varying the hand orientation while keeping the viewing direction constant allows the dissociation of the visual reference frame and the hand-centered reference frame. In the Aligned condition, viewing direction and hand orientation were aligned. In the Orthogonal condition, the hand orientation was instead orthogonal to the viewing direction. With this experimental manipulation the visual reference frame and the hand-centered reference frame were put in misalignment with each other. In an additional condition, the Delay condition, a temporal delay was introduced between exploration of the haptic object and display of the visual one. However, viewing direction and hand orientation were still orthogonal to each other. The latter condition was of interest because several studies suggested that egocentric representations might be recoded over time into more environment-centered representations (Bridgeman et al., 1997; Carrozzo et al., 2002; Rossetti et al., 1996; Zuidhoek et al., 2003).

Several straightforward predictions follow from our experimental conditions. If both visual and haptic spatial information are compared in a unique reference frame, and the common reference frame is, for instance, visual, then we predict response time functions that are invariant to the orientation of the hand. Similarly, if we presume a haptically dominated common reference frame, then the response time function shifts should perfectly match the changes in hand orientation. If, on the other hand, the reference frames, in which visual and haptic information is encoded, directly influence each other, we predict the response time function to partially shift in the direction of the misalignment between the viewing direction and the hand orientation. In addition, a reduction of the size of the shift could be expected as a consequence of the intervening temporal delay.

Materials and Methods

Participants

Ten male participants took part in this experiment. Three of them are authors of the paper. All the others were undergraduate students and were paid for their efforts. None of the participants (except the authors) had any prior knowledge of the experimental design and the task.

Apparatus and Stimuli

The set-up consisted of a large horizontal table in the center of which an iron plate (30 × 30) was positioned. The iron plate was covered with a plastic layer on which a protractor was printed. The center of the protractor was 20 cm from the long table edge. Participants were seated on a stool nearby the longest table edge. The objects used as haptic stimuli were made of two cylindrical bars, with a diameter of 1 cm. The main bar had a length of 20 cm, and attached to this at 5 cm from the center was a smaller bar with a length of 5 cm. One pair of objects had the smaller bar attached on the right side of the main bar, whereas the other pair had it attached on the left side. The main bar had an arrow-shaped end on one side that allowed the orientation to be read off with an accuracy of 0.5°. Small magnets were attached under the bar to prevent accidental rotations. Color photographs of the same objects were used as visual stimuli. Visual stimuli were presented as virtual images in the plane of the table. This was achieved by projecting the images of the objects with an LCD projector onto a horizontal rear projection screen suspended 51 cm above the table. A horizontal front-reflecting mirror was placed face up 25.5 cm above the table. Participants viewed the reflected image of the rear projection screen by looking down in the mirror (see Figure 1). By matching the screen–mirror distance to the mirror–table distance, all projected images appeared to be in the plane of the table. The center of the images of visual stimuli were perfectly aligned with the center of haptic stimuli and the stimuli were matched in size. On a surface 13 cm below the table plane a keyboard was placed which was used to collect participants' responses. For visual stimuli presentation and data collection we used Matlab, using the Psychophysics Toolbox extension (Brainard, 1997).

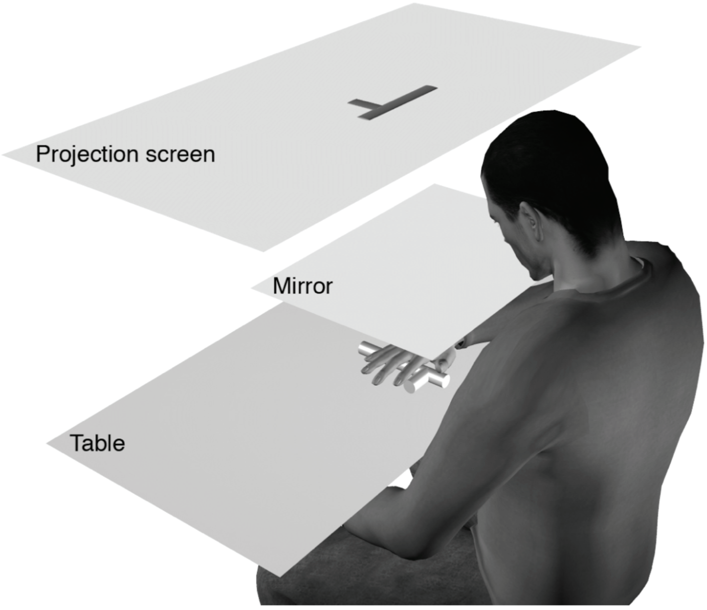


Figure 1. A schematic view of the experimental set-up. The participant looked in the mirror, which was positioned midway between the table and the projection screen. The visual stimulus displayed on the projection screen is seen via the mirror as if it were located on the table exactly in the same location as the haptic stimulus. Both arms are occluded. The right hand explores the haptic stimulus, whereas the left hand controls the keyboard below the table.

Stimuli were presented in pairs: one stimulus haptically and one stimulus visually. The haptic stimulus was oriented at 0°, 90°, 180°, or 270°. An orientation of 0° is parallel to the long table edge; increasing orientation values signify a rotation in counterclockwise direction. The visual stimulus was presented at 18 different orientations, between 0° and 340°, in steps of 20°. Each stimulus was paired with either another identical stimulus (Same trial) or its mirror version (Different trial).

Stimuli were presented in three different experimental conditions. In the Aligned condition the main axis of the right hand exploring the haptic stimulus was aligned with the viewing direction. In the Orthogonal condition the main axis of the right hand was rotated 90° counterclockwise and was thus orthogonal with respect to the viewing direction. In both conditions haptic and visual stimuli were simultaneously explored. In the Delay condition the relation between the exploring hand and the viewing direction was the same as in the Orthogonal condition, but it differed with respect to the timing of the visual stimulus presentation. The visual stimulus was presented with a delay of 5 s after participants stopped exploring the haptic stimulus.

In total, each participant completed 864 trials (2 objects × 4 orientations of the haptic object × 18 orientations of the visual object × 2 same/different pairs × 3 conditions). The order of trials in each experimental condition was random and different for each participant. The order of the experimental conditions was counterbalanced across participants.

Procedure

Participants had to perform a cross-modal visuo-haptic mental rotation task. Before the start of each trial the experimenter set the haptic stimulus and gave a start signal to the participant. Participants were instructed to position their hand in the orientation determined by the experimental condition and touch the haptic stimulus. Participants had no direct view of their arm and hand because these were covered by the mirror and a curtain. As soon as they had identified the distinctive parts of the stimulus they pressed a key with their left hand that made the projector display the visual stimulus. During the presentation of the visual stimulus the right hand was kept in contact with the haptic stimulus. In the Delay condition the visual stimulus was displayed 5 s after the key press. In this period participants lifted their hand from the haptic stimulus but kept it in the same orientation. They had then to respond as fast as possible whether the two stimuli were the same or different. These responses were collected via key presses. It was stressed that the answer should be correct. Participants received feedback on their responses and when an incorrect response was given, the trial was repeated at the end of the experimental condition. Each experimental condition was preceded by practice trials. Experimental sessions ended after one hour to prevent fatigue and participants took on average 2 h to complete all conditions.

Data Analysis

Data analysis was focused on the response times of the Same trials, because the Different trials can be regarded as catch trials. The error rates were low (below 10%) and were not further analyzed.

Fitting Procedure

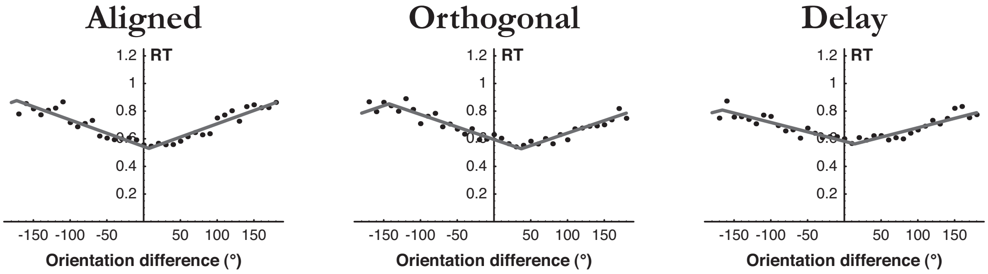
Response times on Same trials were grouped separately for each participant, for each condition, and each orientation difference. For each orientation difference we took the median of the response times. A triangle wave function was then fitted through the data to extract the amplitude, the phase shift and the vertical shift from the response time data. The triangle wave function is a periodic function with a fixed wave period of 360°. We define it as:

$$T\left(x,A,\phi,\mu\right)=2A\left|\operatorname{Int}\left(\frac{x-\phi}{360^\circ}\right)-\frac{x-\phi}{360^\circ}\right|+\mu-\frac{A}{2} \tag{1}$$

where A is the amplitude, ϕ is the phase shift and μ is the vertical shift. The function Int(x) gives the integer closest to x.

Results

Figure 2 represents the response times averaged over participants in the Aligned, Orthogonal and Delay conditions. The fitted lines correspond to the triangle wave function. As it is clear from these graphs, the response time functions are very similar in the three conditions except for their phase shifts. The phase shift is associated with the orientation difference between the haptic and the visual object at which the response times are fastest. From that point response times linearly increase in both positive and negative directions.



Aligned

Orthogonal

Delay

Figure 2. Response times as a function of the orientation difference between the haptic and visual stimuli averaged over all participants for the Aligned, Orthogonal and Delay conditions. A triangle wave function was fitted through the data.

To analyze the differences between conditions we ran a repeated measures ANOVA on the phase shifts with the experimental conditions as a factor. This time the phase shifts were computed for each participant individually. The overall averages are represented in Figure 3. The phase shifts were 2.8°, 33.4° and 7.3° in the Aligned, Orthogonal and Delay conditions, respectively. We found a significant effect of condition ($F(2,18) = 3.714$, $p < .05$). Subsequent pair-wise comparisons with Holm's corrections showed a significant difference between the Aligned and Orthogonal conditions ($p < .05$). The comparisons between the Aligned and Delay conditions and between the Orthogonal and Delay conditions were not significant.

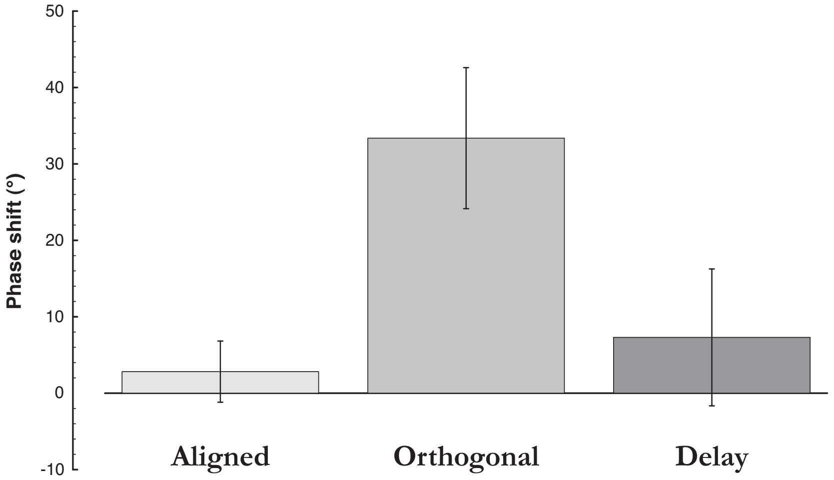


Figure 3. The bars show the average phase shifts (ϕ) in the Aligned, Orthogonal and Delay conditions, and the error bars represent standard errors of the mean.

Discussion

There is general agreement that spatial information is encoded in multiple reference frames both within and across sensory modalities. A less well understood problem concerns the interplay of these diverse reference frames. In the present study, we shed light on how spatial orientational information is encoded in visual and haptic reference frames, and on how these reference frames interact with each other. In our cross-modal mental rotation experiment, we found that the response time function shifted depending on the misalignment between the visual and the hand-centered reference frames. Possibly, a concurring effect of an environmental-centered reference frame has to be also taken into account. Its role was suggested by the counteracting influence on the phase shift after the temporal delay between haptic and visual explorations.

By taking a closer look at the phase shift's changes it is possible to further disclose the interaction of reference frames. The phase shift we found in the Aligned condition was close to 0°. Therefore, when the haptic and visual objects were aligned, the responses were fastest. On the other hand, in the Orthogonal condition we observed a phase shift in the positive direction of about 35°. This phase shift indicates that, contrary to common sense, the haptic and visual objects had to be misaligned by 35° to be quickly identified as being the same. When objects were actually physically aligned response times were longer. Similarly, in the Delay condition a phase shift in the positive direction of about 10° was found. Even though the phase shift was evidently reduced, we did not find it to be significantly different from the Orthogonal condition. However, it was also not significantly different from the Aligned condition. A clear observation can be made about the Orthogonal and the Delay conditions. The direction of the phase shift was congruent with the direction of the misalignment between the viewing direction and the hand orientation, but the magnitude of the phase shift was smaller than the misalignment itself. It is almost as if the visual object was encoded with respect to the viewing direction, the haptic object with respect to the hand, and finally these two spatial encodings were directly compared. The modality-specific reference frame thus strongly influenced each other, and the outcome might be seen as the product of this interaction. Moreover, the interaction between reference frames seems to change over time. It is very likely that many more reference frames are simultaneously involved in the encoding of spatial information. However, we suggest that the visual, the hand-centered and the environment-centered reference frames are the dominant ones.

Previous unimodal mental rotation studies reported a substantial reference frame influence on the way spatial information is encoded and compared, both in vision and in haptics (Carpenter & Eisenberg, 1978; Corballis et al., 1976, 1978; Volcic et al., submitted). Here, we presented the novel finding that cross-modal comparison of objects is a consequence of how visual and haptic spatial information is encoded. In this respect, our results remind of the viewpoint-dependent performance encountered in cross-modal object recognition (Newell et al., 2001; Ernst et al., 2007). Although mental rotation and recognition of rotated objects show behaviorally similar effects, they are most likely to rely on different processes (Tarr & Pinker, 1989). However, object recognition was shown to be viewpoint-specific in vision as well as in haptics. Whereas visually the optimal view was identified as being the side of the objects facing the observer, the optimal view in haptic domain was shown to be the back of the objects. Moreover, for cross-modal recognition, performance was better when the front view from the visual representation matched the back view of the haptic representation. Likewise, in our study the cross-modal identification of objects was fastest when the viewed and touched objects had a similar orientation with their respective modality-specific reference frame.

In sum, we showed that spatial orientational information is encoded within modality-specific reference frames and that performance in a visuo-haptic cross-modal mental rotation task is bound to the relative alignments of reference frames and their interactions. In addition, the intervening temporal delay is presumed to have affected the relative influence of reference frames. These findings challenge the notion of a common reference frame, be it either visual or haptic, and suggest direct influences among different sensory modalities.

Chapter 7
Summary and Conclusions

Summary

The present thesis focused on haptic spatial processing. In particular, our interest was directed to the perception of spatial relations with the main focus on the perception of orientation. To this end, we studied haptic perception in different tasks, either in isolation or in combination with vision. The parallelity task, where participants have to match the orientations of two spatially separated bars, was used in its two-dimensional and three-dimensional versions in *Chapter 2* and *Chapter 3*, respectively. The influence of non-informative vision and visual interference on performance in the parallelity task was studied in *Chapter 4*. A different task, the mental rotation task, was introduced in a purely haptic study in *Chapter 5* and in a visuo-haptic cross-modal study in *Chapter 6*. The interaction of multiple reference frames and their influence on haptic spatial processing were the common denominators of these studies. In this final chapter, the most important findings of the foregoing chapters are summarized and general conclusions are drawn.

In *Chapter 2*, haptic spatial processing was investigated via the bimanual parallelity task on the frontoparallel plane. An extensive set of spatial locations was used to monitor how systematic deviations from veridicality occur and evolve on the whole plane. Moreover, the orientations of the hands exploring and setting objects were measured to identify the role of a hand-centered egocentric reference frame that was assumed to be the origin of the deviations. First, we found a correlation between deviations and hand postures. This finding was in support of a biasing influence of the hand-centered reference frame on haptic spatial processing. Second, we observed the occurrence of the oblique effect (i.e., smaller deviations for cardinal than for oblique orientations). However, participants with larger deviations showed a reversal of this effect. It was suggested that cardinal orientations, on which performance is better should thus be defined with respect to the perceptual reference frame and not with respect to the environment. In general, the results of the parallelity task on the frontoparallel plane were in agreement with the hypothesis that the magnitude of the deviations is affected by the degree to which the egocentric and the allocentric reference frame combine with each other.

The previous study was the last of a series in which the systematic deviations occurring in the parallelity task were mapped on the horizontal, midsagittal and frontoparallel planes. Our next step was to explore haptic perception of spatial relations in three-dimensions. *Chapter 3* was devoted to this issue. Participants had to construct a field of parallel bars that could be oriented in three-dimensions. The systematic deviations observed in this study were comparable to those found in the two-dimensional version of this task. Subsequently, we tried to investigate if a model based on the weighted average of an egocentric and an allocentric reference frame could provide an appropriate description well these patterns of deviations. Moreover, we compared models based either on a hand- or body-centered egocentric reference frame. The hand-centered weighted average

model successfully captured the systematic pattern of deviations. Therefore, the role of the hand-centered reference frames was confirmed also in the three-dimensional haptic parallelity task.

Chapter 4 addressed the issue of whether and how concurring visual information can influence performance in the haptic parallelity task. In our first experiment we provided a baseline measure of performance at this task, while in the second and third experiments we assessed the changes brought about by adding non-informative vision and incongruent visual information, respectively. We showed that non-informative vision has an ameliorating effect on performance, though this was not equally distributed across participants. Those that already demonstrated better performance in the baseline condition benefited more than those participants that showed larger deviations. Similarly, haptic performance was influenced by the simultaneously presented incongruent visual information. Again, interfering visual information had a stronger impact on the participants with smaller deviations than on those that performed worse in the baseline condition. We suggested that the visual information was integrated with the haptic information, even though participants were aware that the additional visual information was irrelevant for the tasks at hand. Interestingly, the degree to which visual information was taken into account was shown to be inversely related to the biasing influence of the egocentric reference frame.

A different task, the haptic mental rotation task, was employed in *Chapter 5*. Participants had to haptically compare the parity of two objects. These objects were located at distinct spatial locations and were explored by keeping the hands in specified orientations that were different for the various conditions. Response times were collected for each judgment and then fitted with a triangle wave function. From the phase shifts of the response time functions in the different conditions it was possible to derive the reference frames in which the objects were encoded and compared. Our previous results suggested that several reference frames are involved in this process. We considered an allocentric, a hand-centered and a body-centered reference frame as the reference frames most likely to be involved in haptic spatial processing. Each of them contributed to a certain degree, but the hand-centered reference frame proved to be the most influential. The possibility that a single reference frames drives haptic spatial processing was discarded.

In *Chapter 6*, the influences among reference frames were explored in a visuo-haptic cross-modal mental rotation task. One object was presented haptically and one visually. Both objects were perceived as being in exactly the same spatial location due to the design of our set-up. Participants had to assess if the two objects were the same or mirror versions of each other. The orientation of the exploring hand with respect to the viewing direction was manipulated in two conditions. In an additional condition, a temporal delay was introduced between the presentation of haptic and visual information. From the phase shifts of the response time functions we were able to show how the spatial information encoded in different sensory modalities and in different reference frames is combined. We did not observe any phase shift when the viewing direction and the hand orientation were aligned. However, when the viewing direction and hand orientation were orthogonal to each other, a phase shift corresponding to approximately half of the misalignment was found. Moreover, a reduction in this phase shift was measured as a consequence in the intervening temporal delay. Our results showed that visual and haptic reference frames directly influence each other and that these influences can change over time.

Conclusions

Manipulating objects, exploring the relations between them and interacting with the surrounding environment require the encoding and processing of spatial information. Objects can be encoded in different reference frames, but which of these, or which combination of them, is used for a particular need might depend on specific circumstances. In this thesis we approached the problems of which reference frames play the major role in haptic spatial processing and how the relative roles of distinct reference frames change depending on the available information and the constraints imposed by different tasks.

A number of studies have focused on the perception of spatial relations, by introducing tasks in which participants are required to orient an object to perceive it as parallel, perpendicular or mirrored to another one (Kappers, 1999, 2004; Kappers & Koenderink, 1999). These investigations were not limited to the horizontal plane, but were extended also to the midsagittal and the frontoparallel plane (*Chapter 2* in this thesis; Hermens et al., 2006; Kappers, 2002). Similar deviations were observed both in unimanual and bimanual experiments. For instance, in the parallelity task the two objects were perceived as parallel when in fact they diverged on average by 50°. These consistent patterns of deviations point towards a common origin. The first insight into the probable cause of the error patterns was due to a straightforward observation: if the deviation at a particular location is in the clockwise direction, the hand at that particular location is rotated clockwise with respect to that of the hand at the location of the reference object. Given that the hand is our primary tool of haptic interaction with the environment, its influence was not surprising. However, the fact that error patterns seem to revolve around the trunk did not exclude a role of the body (Kaas & van Mier, 2006).

On the basis of the foregoing, it was proposed that the error patterns result from the use of a biasing egocentric reference frame where an allocentric one should have been used (*Chapter 2* in this thesis; Kappers, 2003, 2004). The egocentric reference frame has been assumed to be fixed to either the hand or the body, and the allocentric reference frame to the environment. Many references to the ample literature that supports the existence and use of multiple reference frames have already been given throughout this thesis; therefore, in these conclusions I approach the hypothesis of multiple reference frames in the context of haptic spatial processing only. Most studies on haptic parallelity have shown that the deviations correlate with hand orientation (Kappers, 2005). This correlation was shown also in the study on the frontoparallel plane described in *Chapter 2*. In an attempt to identify the role of the hand-centered reference frame, Kappers and Viergever (2006) explicitly instructed participants to orient their hands in a predetermined way during the execution of the task. Participants kept their hands in an aligned, a convergent or a divergent position. The orientation of the hands with respect to the objects had an impact on the magnitude of the deviations. When the hands converged, the deviations decreased, and when they diverged, the deviations increased. When the hands were aligned, the deviations were intermediate to the previous two conditions. However, performance was still non-veridical. Although the hand-centered reference frame proved to have a dominant influence, the residual deviations indicated also an influence of the body-centered reference frame.

The use of an egocentric reference frame explained the direction of the deviations, but it did not capture the magnitude of the deviations. The magnitudes that were measured were smaller than those expected if only an egocentric reference frame was used. The error patterns developed as if an interaction between a purely egocentric and an allocentric reference frame was taking place. Therefore, a weighted average model that combines the reference frames was proposed (Kappers, 2007). Two alternative models were contrasted in this two-dimensional haptic parallelity study. The models were based on a weighted average between an allocentric and egocentric reference frame, but in one case the egocentric reference frame was hand-centered, and in the other case it was body-centered. Both alternative models fitted the data well, but the hand-centered based model captured the error patterns more accurately. Similarly, in *Chapter 3* different models were tested in the three-dimensional haptic parallel matching. In this case the advantage of the hand-centered weighted average model was even more distinct. Basically, the weighted average model defines a continuum between the reference frame fixed to the environment and the one fixed to the hand. Participants' performance always falls in this range. On average, in both the two-dimensional and in the three-dimensional study the participants' performance shifted by approximately 20–25% from the allocentric reference frame towards the egocentric reference frame.

Performance in haptic spatial processing has been shown to depend also on sources of information or processing that are not strictly connected to the task at hand. For instance, non-informative vision improved performance, as did a temporal delay between the acquisition of the spatial information and the subsequent use of this information (*Chapter 4* in this thesis; Newport et al., 2002; Zuidhoek et al., 2003, 2004). These improvements were interpreted as shifts from the egocentric to the allocentric reference frame. In other words, the contributions of the reference frames were assumed to change due to the experimental manipulations that allowed the participants to build a more reliable representation of the surrounding environment. However, additional sources of visual information did not only show to improve performance, but also to parametrically influence haptic performance. By simultaneously providing incongruent visual and haptic information about the orientation of an object, the deviations participants made were biased in the direction of the visually presented bar (*Chapter 4* in this thesis; Kaas et al., 2007).

Importantly, the studies described in *Chapter 5* and *Chapter 6* showed that the interacting reference frames are not of exclusive importance in the haptic parallelity task only, but rather they evince themselves also in other haptic and cross-modal tasks. The spatial information needed to solve the mental rotation task was also shown to be encoded with respect to different reference frames. However, the different task demands and temporal constraints induced a strong dominance of the hand-centered reference frame and almost a disappearance of the contribution of the allocentric reference frame. The study on haptic mental rotation suggested that the contributions of reference frames cannot be limited to just a hand-centered and an allocentric reference frame. This fact was even clearer in the cross-modal mental rotation task where several visual and haptic reference frames appear to interact. The most likely possibility is that a whole hierarchical structure of reference frames exists and some of these emerge as the dominant ones depending on the demands and the circumstances of the surrounding environment and the needs of an active perceiver.

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Nederlandse samenvatting

Dit proefschrift concentreert zich op de haptische verwerking van ruimtelijke informatie. We waren met name geïnteresseerd in de waarneming van ruimtelijke relaties en meer in het bijzonder in de waarneming van oriëntatie. Hiertoe hebben we een aantal taken onderzocht die ofwel zich enkel tot de haptische modaliteit beperkten ofwel de haptische met de visuele modaliteit combineerden. De paralleltaak, waarin proefpersonen twee ruimtelijk gescheiden staafjes gelijke oriëntatie dienen te geven, is in zijn tweedimensionale en driedimensionale vorm onderwerp van respectievelijk *Hoofdstuk 2* en *Hoofdstuk 3*. De invloed van niet-informatieve visuele input en interferentie van visuele informatie op prestaties in de paralleltaak is bestudeerd in *Hoofdstuk 4*. Een andere taak, de mentale-rotatietaak, is in een puur haptische studie geïntroduceerd in *Hoofdstuk 5* en in een visueel-haptische studie in *Hoofdstuk 6*. De interactie van verschillende referentiestelsels en de invloed daarvan op de haptische verwerking van ruimtelijke informatie waren de gemeenschappelijke delers van al deze studies.

In dit proefschrift behandelden we de vragen welke referentiestelsels een belangrijke rol spelen in de haptische verwerking van ruimtelijke informatie en hoe de relatieve bijdragen van de verschillende referentiestelsels veranderen afhankelijk van de beschikbare informatie en de beperkingen gesteld door de verschillende taken. We vonden dat de invloed van een referentiestelsel gecentreerd op de hand de belangrijkste oorzaak was van afwijkingen van veridicaal, zoals gevonden in zowel de twee- als de driedimensionale studies. De resultaten konden worden beschreven door een gewogengemiddelde-model, waarin het handgecentreerde egocentrische referentiestelsel verondersteld wordt een vervormende invloed op het allocentrische referentiestelsel te hebben. Het is aangetoond dat prestaties in de haptische verwerking van ruimtelijke informatie ook afhangen van bronnen van informatie of verwerking die niet strikt samenhangen met de taak. Wanneer niet-informatieve visuele input werd gegeven, werd een gunstige effect op haptische prestaties waargenomen. Deze verbetering werd geïnterpreteerd als een verschuiving van een egocentrisch naar een allocentrisch referentiestelsel. Bovendien, interfererende visuele informatie die vlakbij de haptische stimulus werd aangeboden, moduleerde de grootte van de afwijkingen parametrisch. De invloed van het handgecentreerde egocentrische referentiestelsel bleek ook uit de haptische mentale-rotatietaak, waarin proefpersonen de pariteit van twee voorwerpen sneller konden beoordelen wanneer deze gelijke oriëntatie hadden ten opzichte van de handen dan wanneer ze gelijke fysische oriëntatie hadden. Op vergelijkbare wijze werd in de visueel-haptische mentale-rotatietaak de inschatting van de pariteit beïnvloed door de oriëntatie van de tastende hand ten opzichte van de kijkrichting. Dit effect bleek gemoduleerd te worden door een tussenliggende tijdsvertraging die verondersteld wordt de invloed van het handgecentreerde egocentrische referentiestelsel tegen te gaan.

We stellen voor dat het handgecentreerde referentiestelsel ingebed is in een hiërarchische structuur van referentiestelsels, waarin bepaalde stelsels meer prominent zijn afhankelijk van de eisen en omstandigheden van de omgeving en de behoeften van de actieve waarnemer.

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Curriculum Vitae

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