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Haptic perception of parallelity

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Abstract: Research has shown that the haptic perception of orientation is susceptible to systematic spatial bias. Large and systematic deviations have been found in haptic parallelity matching tasks supporting a reference frame based model. It has been suggested that the observed deviations result from the use of a frame of reference that is intermediate to an allocentric and an egocentric reference frame. The systemic bias of the deviations seems be caused by the strong bias produced by the hand-centered egocentric reference frame. In this paper results of studies are discussed showing a strong evidence for the abovementioned model in which egocentric representations exist in parallel to allocentric ones, and in which the former is biased by a hand-centered reference frame. The extent to which each representation is used appears to depend on factors like orientation, distance, gender, task instruction, practice and training. Manipulations stimulating allocentric processing or reducing egocentric processing have been shown to affect haptic parallelity performance.

Keywords: Haptic Perception, Egocentric, Allocentric, Reference Frame, Gender, Delay, Vision

1. Introduction

Humans are constantly interacting with objects is their environment. To locate or orient an object in peripersonal space, visual, haptic, and auditory information of the object can be used in such a way that one is able to reach for it, grasp it, manipulate it and/or use it. Our sensory modalities extract spatial information of the object, which is encoded in relation to a certain reference. If this reference is coded with respect to the own body, it is referred to as egocentric or body centered referencing. Allocentric or object-centered referencing, on the other hand, is referred to when the location of an object is coded in relation to another object and without reference to the body. In the former an egocentric reference frame is used to specify the location or orientation of the object, with space being represented internal to the perceiver, in the latter an allocentric reference frame is used in which space is represented external to the perceiver and independent of the position of the perceiver (Klatzky, 1998). An accurate representation of peripersonal space seems crucial for successful interaction with objects in this space. Contrary to what one would expect, our perception of space is not veridical. This pertains to the visual modality (Cuijpers, Kappers, & Koenderink, 2000; Hermens & Gielen, 2003; Henriques, Flanders, & Soechting, 2005) as well as to the haptic modality (Kappers, 1999; Luyat, Gentaz, Corte, & Guerraz, 2001; Henriques, Flanders, & Soechting, 2004).

It seems obvious that when visual input is not available, the haptic sense plays an important role in providing information about the space and objects around us. However, haptic spatial representations are prone to errors, meaning that what we feel as having the same line length (Lanca & Bryant, 1995; Marks & Armstrong, 1996), path length (Lederman, Klatzky, & Barber, 1985), shape (Henriques & Soechting, 2003) or orientation (Appelle & Countryman, 1986; Kappers, 1999; Luyat et al., 2001) deviates from what is physically the same. Already in the first part of the previous century researchers reported that haptic space is distorted in relation to physical space (Blumenfeld, 1937, Von Skramlik, 1937). It was not until later in that century that the metric of haptic space interested other researchers who concluded that haptic distance estimates are not Euclidean (Brambring, 1976; Lederman et al., 1985). At the end of the century the judgment of haptic spatial relations was studied in more detail by Kappers and Koenderink (Kappers, 1999; Kappers & Koenderink, 1999). They used a so-called haptic parallelity task in which blindfolded participants were instructed to align two bars in such a way that the orientation of a test bar, presented in a random orientation at another location, felt parallel to the orientation of a reference bar, which was oriented by the experimenter. Significant deviations from the veridical orientations were found and it was shown that what participants feel as being parallel is distorted from what is physically parallel. The distortions or deviations turned out to be not only large but also showed a systematic directionality in the (natural) orientation of the hand. When a bar had to be paralleled at the right side of the participant, deviations were mainly in clockwise direction, when the bar was at the left side, deviations were mostly directed counter-clockwise (Kappers, 2004).

These deviations have been observed in haptic parallelity tasks performed in different planes, like the (mid)horizontal plane (e.g. Kaas & Van Mier, 2006, Kappers, 1999; Kappers & Koenderink, 1999; Newport, Rabb, & Jackson, 2002; Zuidhoek, Kappers, Van der Lubbe, & Postma, 2003; Van Mier, 2013), the frontoparallel plane (Hermens, Kappers, & Gielen, 2006; Volcic, Kappers, & Koenderink, 2007), the midsagittal plane (Kappers, 2002; 2004), the three-dimensional plane (Volcic & Kappers, 2008) and for both unimanual and bimanual responses (Kappers & Koenderink, 1999; Kappers, 2002). A study by Fernández-Díaz and Travieso (2011) even found large and systematic deviations when the parallelity task was performed in rear peripersonal space (behind the back of the participant), with deviations clearly being influenced by the natural orientation of the hand. Furthermore, making two bars collinear or perpendicular to each other resulted in deviations comparable to making the bars parallel (Kappers, 2002; 2004; Kappers & Koenderink, 1999). In a recent study by Coleman & Durgin (2014) participants had to bimanually match the slope of a reference board that was felt with the left hand to that of a test board adjusted by the right hand in a sagittal plane. The results showed that the deviations in this haptic perception task of surface orientation reflected an egocentric bias comparable to those found in tasks where bar orientations had to be matched.

The magnitude of the deviations has been found to be participant-dependent, meaning that although all participants showed systematic deviations, the range of those deviations varied between participants and was found to be very broad. Van Mier (2013) found inter-individual variations with deviations ranging from 3° to 44° over participants. In a study by Kappers (2003), the deviation between the bars averaged over 68 subjects was 41°, but the size of the deviation ranged from 8° to 91°, showing a great inter-individual variation in deviation size. This variation has been reported in many other studies (Kappers, 2004; 2007; Kappers & Liefers, 2012; Kappers, Postma, & Viergever, 2008; Kappers & Schakel, 2011; Kappers & Viergever, 2006; Volcic, Van Rheede, Postma, & Kappers, 2008; Zuidhoek et al., 2003), and was not accounted for by factors as arm length (Van Mier, 2013) and span, or shoulder width (Kappers, 2003). Furthermore, no differences regarding systematic directionally were observed for left-handed participants compared to right-handers (Kappers, 2003). Despite these large errors, participants were convinced that both bars had the same physical orientation in space.

2. Reference Frames

As stated before, when manipulating objects in peripersonal space we can use allocentric or egocentric reference frames. Using an allocentric reference frame in the haptic parallelity task would result in veridical performance, with both bars being physically parallel. However, the (often) large and systematic deviations that are found in this task imply that participants do not (only) use an allocentric reference frame. On the other hand, the deviations are smaller than the rotations of the hand when one would (only) favor an egocentric reference frame (Kappers, 2002; 2003). Following the suggestion of Soechting and Flanders that performance in reaching and grasping tasks is most likely determined by an intermediate frame of reference (Flanders & Soechting, 1995; Soechting & Flanders, 1992), Kappers proposed the same for haptic spatial matching tasks (Kappers, 2002). She suggested that what is haptically perceived as being parallel seems to be determined in a frame of reference intermediate to an egocentric frame centered on the body and an allocentric frame anchored to external space (Kappers, 2002; 2003). Making two bars perpendicular to each other resulted in similar deviations as making them parallel, with a mean deviation of 38.2° for parallel matching and 37.4° for making the bars perpendicular to each other (Kappers, 2004). It was assumed that for both tasks the outcome depends on the reference frame used, with the biasing influence of the egocentric reference frame being the same for perpendicular and parallel matching. The use of an intermediate reference frame can explain why the size of the deviations is participant dependent, since it depends on the extent to which the haptic performance of a subject is dominated by an egocentric reference frame. If a subject relies more on an egocentric frame of reference, large deviations can be expected in the parallelity task, because within this reference frame haptically parallel would be defined as “the same orientation with respect to the hand”. If, however, a subject relies more on an allocentric frame of reference, haptically parallel would also be close to physically parallel. The errors observed in haptic parallel matching suggest that an egocentric reference frame biases judgments of allocentric space. The deviations seem to be the result of a combined use of egocentric and allocentric reference frames (see figure 1). What is perceived as perceptually parallel is the weighted average of both frames, with the weight (i.e., how much both reference frames contribute), depending on the task and/or participant (Kappers, 2004; 2007; Kappers & Viergever, 2006; Van Mier, 2013; Volcic et al., 2007; 2008).

In the parallel-setting task, the output is a combination of haptic orientation perception and haptic orientation production, and it therefore makes sense that a reference frame intermediate between an egocentric and an allocentric one is used. Hermens and colleagues (2006) hypothesized that parallel matching involves three stages: 1. perception of the orientation of both bars, 2. transfer of the perceived orientation of the reference bar to the location of the test bar, and 3. the production of the transferred orientation at the test bar. Because there is no visual input, the first phase of haptic input processing requires necessarily an egocentric frame of reference because the sensory input is channeled through the hands (Zuidhoek, Kappers, & Postma, 2007). This information then has to be transferred to the other hand to match the orientation. When participants either had to verbally report a perceived orientation or had to set a verbally presented orientation, significantly smaller deviations were observed in these conditions than in parallel matching (Hermens et al., 2006; Zuidhoek, Kappers, & Postma, 2005; 2007). Because the sum of the deviations in both tasks (perception and production) was smaller than the deviations in the parallel task, Hermens and colleagues (2006) suggested that the deviations must be the result of the transfer of the perceived reference orientation to the location of the matching bar, even when taking into account that the parallel task was performed bimanually while the perception and production tasks involved unimanual performance. Another explanation given by Hermens et al. (2006) is that participants might have mainly used an allocentric reference frame in the perception and production tasks, while in the parallel matching task both an ego- and an allocentric frame was used.

Taken the above into account, one would expect that when the use of an egocentric reference frame would be beneficial or comparable to an allocentric reference frame, performance should be more accurate or close to veridical. This is indeed what has been observed when participants were instructed to position the test bar in such a way that the reference bar and the test bar formed each other's mirror image. In this so-called haptic mirror task, which was performed in the mid-horizontal plane, small and random deviations have been reported (Fernández-Díaz & Travieso, 2011; Kaas, Van Mier, & Goebel, 2007a; Kaas, Van Mier, Lataster, Fingal, & Sack, 2007b; Kaas & Van Mier, 2006; Kappers, 2004; 2007; Van Mier, 2013). In contrast to the parallelity task in which large and systematic deviations have been found, in the mirror task deviations were small and random. These differences in size of deviations might be explained by the reference frame being used by the participants. In the mirror task, using the same configuration for the hands by mirroring the setting of the hands to each other by utilizing an egocentric reference frame, results in the same high level of accuracy as the use of an allocentric reference frame (Kappers, 2004; 2007). For mirror matching the use of both reference frames would correspond to the setting of the test bar shown in C in figure 1.

To summarize, the size and direction of the deviations found in haptic parallelity matching strongly suggest a reference based model, in particular, an intermediate reference frame model, with involvement of egocentric as well as allocentric representations.

3. Nature of the Egocentric Reference Frame in Haptic Parallelity Matching

When one refers to an egocentric reference frame regarding haptic performance, it is important to establish on which body part(s) the reference frame is centered. Luyat and colleagues have suggested a hand- and shoulder-centered reference frame for haptic tasks (Luyat, et al., 2001; Luyat, Moroni, & Gentaz, 2005), while others have proposed an arm-centered (e.g. Blumenfeld, 1937; Flanders & Soechting, 1995; Soechting & Flanders, 1992) and a body-centered (e.g. Millar & Al-Attar, 2004) frame of reference. Results reported by Kappers and Viergever (2006) support a hand-centered egocentric reference frame with respect to haptic parallelity matching. In this study participants were instructed to perform the haptic parallelity task using different hand orientations, with their hands being either oriented straight ahead, rotated to the left, to the right, outwards or inwards. They found that the size of the deviations was strongly influenced by the relative orientation of the hands as predicted by a predominantly hand-centered egocentric frame of reference. However, as the authors state, an additional but much smaller influence of the body-centered frame could not be excluded. In a follow-up to the abovementioned study, Kappers and Liefers (2012) asked participants to perform the parallelity task at the same position horizontally by presenting the bars in front of the body midline, with reference and test bar being 12 cm apart vertically. This set-up excludes the influence of a body-centered reference frame. The angle between the arms/hands was systematically varied from 40° to 180°. Systematic deviations were found that correlated positively and significantly with the angle between the arms/hands and strongly suggest a hand/arm centered egocentric reference frame.

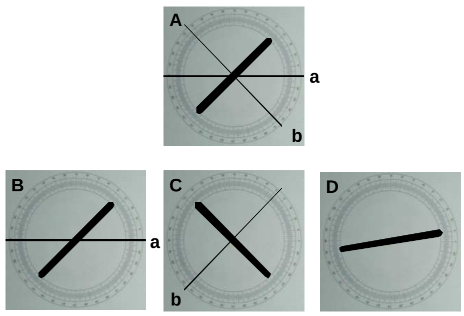

Figure 1. *Illustration of hypothetical responses in haptic parallelity when using different reference frames. A. The orientation of the reference bar that was explored with the left hand and had to be paralleled by the participant with the right hand on the test bar. B. Orientation of the test bar when a purely allocentric reference frame would have been used. Both bars have the same physical orientation with respect to an allocentric reference frame, e.g. the horizontal side of the table (a). Parallel matching would have been veridical. C. Orientation of the test bar when using a purely egocentric reference frame. Here both bars have the same orientation with respect to the participant's ego center, in this case the hands (b). Parallel matching would have shown deviations that corresponded to the natural orientation of the hand at the location of the test bar. D. Typical orientation of the test bar by a participant, with the setting of the bar being intermediate between allocentrically and egocentrically parallel.*

Additional evidence for a hand-centered egocentric reference frame was found by Volcic and Kappers (2008) using a three-dimensional unimanual parallelity task. Participants had to make eight test bars, which could be oriented in three dimensions, parallel to a reference bar. The orientations of the bars were specified by the tilt and slant angles. Also in this task, the deviations could be best described by a hand-centered weighted average model in which a weighted egocentric biasing effect of the hand on the allocentric frame of reference is assumed. Using a haptic mental rotation task, Volcic, Wijntjes and Kappers (2009) explored the nature of the reference frame in a recognition task instead of a manipulation task. In this study participants bimanually explored two bars of 20 cm length that each had a smaller bar attached at the top. The smaller bar could be attached on the right or left side of the main bar, resulting in a task comparable to the Shepard and Metzler mental rotation task. Both bars were set at a predefined but different orientation, and participants had to keep both hands in a divergent, convergent or aligned orientation. Participants had to state if both bars were the same or different. The results were in line with the proposition of an interaction between an allocentric and egocentric reference frame. With respect to the latter, a hand- and body-centered reference frame contributed to the haptic processing, although the hand-centered frame was found to be the most dominant.

Kappers (2007) asked her participants, after they had finished the parallelity task, to place their hands in a natural way at the locations at which they also had performed the parallel-setting task. The direction of the middle finger was defined as the orientation of the participant's hand-centered reference frame for each location. She compared the orientations of the hand settings with the orientations in the parallelity task for each participant and fitted the results to a hand- and body-centered model. She found that for 8 of the 10 participants the results were best described by a hand-centered model, while a body-centered model outperformed the hand-centered model for only 2 participants. Volcic and colleagues (2007) reported a similar correlation between hand orientation differences and parallelity deviations in the frontoparallel plane.

Van Mier (2013) showed that when the egocentric bias of the hands was reduced in the parallelity task, deviations were considerably smaller. When participants were instructed to parallel the orientation of the reference bar by drawing instead of setting the orientation of the test bar, deviations were reduced up to 70%. Because the drawing movements were directed by the arm/shoulder, the hand was mainly used to hold the pen, thereby reducing the bias of hand when matching the orientation of the reference bar.

In sum, the outcome of the abovementioned studies implies that performance in the haptic parallelity task is most likely influenced by the use of a mainly hand-centered egocentric reference frame.

4. Factors Affecting Parallelity Matching

Several factors have been reported that affected the extent in which ego- and allocentric processing influenced haptic parallelity performance. It has been found that performance deviated more from veridicality when the horizontal distance between the hands was increased and when oblique orientations had to be matched compared to cardinal orientations (e.g. Kaas & Van Mier, 2006; Kappers, 1999, 2002; 2003; Van Mier, 2013). Additionally, the magnitude of the deviations has been found to be influenced by task instruction (Kaas & Van Mier, 2006; Van Mier, 2013). A combination of training and feedback resulted in a marginally improvement (Kappers, et al., 2008).

4.1. Distance between and Orientation of the Bar(s)

An interesting observation has been that deviations in haptic parallelity showed a horizontal gradient, but not a vertical gradient. Deviations from parallel increased (linearly) when the distance between the reference and test bar increased in the horizontal direction (Fernández-Díaz & Travieso, 2011; Kaas & Van Mier, 2006; Kappers 1999, 2002, 2003; Kappers & Koenderink, 1999; Van Mier, 2013; Zuidhoek et al., 2003), but not when the distance was changed vertically (Fernández-Díaz & Travieso, 2011; Kappers & Koenderink, 1999). This finding is additional evidence for the biasing effect of the hand-centered egocentric reference frame. When the horizontal distance between the bars is increased, this affects not only the distance with respect to the body (Kaas & Van Mier, 2006), but also the orientation of the hands (Kappers & Viergever, 2006).

Remarkably, the magnitude of the deviations in the haptic parallelity task has also been found to be dependent on the orientation of the bar. It has been shown that most participants have smaller deviations when matching cardinal orientations of 0° and 90° than when matching oblique orientations like 45° and 135°. This so called oblique effect, first observed and described by Appelle (1972) for the visual domain and later replicated by Lechtelt, Eliuk and Tanne (1976) for the haptic domain, reflects a generally faster and also more accurate processing of stimuli aligned with vertical and horizontal orientations than with oblique orientations. The haptic oblique effect has been observed in studies using an exploration-reproduction task (e.g. Gentaz & Hatwell, 1995; Hermens et al., 2006; Kaas & Van Mier, 2006; Kappers, 1999; 2002; 2003; 2004; Kappers & Viergever, 2006; Lechtelt & Verenka, 1980; Van Mier, 2013; Volcic et al., 2007). An important observation is that the reference frame one relies on plays a crucial role in the presence of the oblique effect. This means that oblique orientations and cardinal (horizontal and vertical) orientations are defined with respect to a reference frame and, consequently, do not have to be the same for allocentric and egocentric frames of reference. Thus, if a participant relies more on an allocentric frame of reference, the oblique effect will lead to larger deviations for 45° and 135° orientations, since those are considered as oblique orientations (Kappers, 2003; 2007). However, for a more egocentrically oriented participant, 45° and 135° orientations are aligned with the hand and therefore are cardinal with respect to the egocentric reference frame. This leads to a reverse oblique effect: deviations for cardinal orientations are larger than those for oblique orientations (Kappers, 2003). This effect can be expected primarily when the hand is placed at a larger distance with respect to the body, since the hand is then oriented more obliquely than at a shorter distance. Participants showing large deviations in the parallelity task most likely rely more on an egocentric reference frame, whereas participants with only small deviations might rely more on an allocentric frame of reference. As a consequence, for egocentrically oriented participants with large deviations, the oblique effect should reverse. This was indeed observed in several studies (Hermens et al., 2006; Kappers, 2003; 2004; Kappers & Viergever, 2006; Volcic et al., 2007). Thus, the occurrence of the (reverse) oblique effect is also providing further evidence for the existence of an intermediate frame of reference; an oblique effect is expected when participants rely more on an allocentric reference frame, whereas a reverse oblique effect is expected for participants giving higher weight to the egocentric reference frame. Additionally, these findings support a hand-centered egocentric reference frame.

4.2. Influence of Task Instruction

That the size of the deviations can also be dependent on the task instruction has been shown in studies by Fernández-Díaz and Travieso (2011), Kaas and Van Mier (2006), Kappers (2004) and Van Mier (2013). In these studies participants performed a regular haptic parallelity task as well as a haptic mirror task. In both tasks, matching a 90° (vertical) orientation involves the same setting of the bar and positioning of the hands, regardless if the test bar had to be made parallel or mirrored to the reference bar. One would expect that therefore the deviations at the 90° orientation would be more or less the same. When Kaas and Van Mier (2006) and Van Mier (2013) directly compared deviations at this orientation in the parallel and mirror task they found that making the bars parallel resulted in significantly larger deviations than mirroring the bars. This difference is also clearly apparent in the data of Fernández-Díaz and Travieso (2011) and Kappers (2004), although they did not statistically compare the deviations. These results indicate an intra-individual weighting of the egocentric and allocentric reference frames depending on the experimental task instruction.

4.3. Influence of Training and Feedback

When performing the haptic parallelity task, participants usually don't receive feedback regarding their performance and the orientation of the test bar and deviations reported so far have been based on 3 to 5 repetitions only for a particular orientation. Because most humans do not have much experience with haptic parallelity matching, it brings up the question if deviations would be smaller or even eliminated, once participants were given information about the task, feedback about their settings and/or were able to practice the task. Hermens et al. (2006) showed that being informed about the task did not influence performance. They compared the deviations of participants who had prior knowledge about the systematic errors in this task with naive participants without this knowledge and found that the deviations were not significantly different. Additionally, Kappers and coworkers (2008) found that the deviations were only marginally affected by training and feedback. Without informing their participants about their biased performance, they studied the effects of visual training (seeing the correct orientations), haptic training (feeling the correct orientations) and combined visuo-haptic training (seeing and feeling the correct orientations). In addition they studied the effect of error feedback on the performance of the participants, again under visual, haptic and visual-haptic conditions. They showed that the robustness of the deviations persisted even after participants received haptic and/or visual feedback and training. Haptic or visual training did not significantly decrease the magnitude of the deviations, only combining both training modes resulted in a small but significant improvement. This improvement was explained by a more pronounced reliance on an allocentric reference frame. Although providing participants with haptic and visual feedback about their errors reduced the deviations, performance was still far from being veridical, showing that the egocentric component of the reference frame was still persistent. As the authors state, it might be that extension of the feedback phase would eventually lead to more veridical parallel matching.

5. Task Manipulations Affecting Allocentric and Egocentric Processing

If haptic parallel matching is indeed influenced by ego- as well as allocentric reference frames, it might be expected that manipulations favoring more allocentric processing, or minimizing egocentric processing, would result in smaller deviations. Several studies have provided evidence that this is certainly the case. A shift to the use of more allocentric processing by introducing a delay between exploration and matching (Postma, Zuidhoek, Noordzij, & Kappers, 2008; Zuidhoek et al., 2003; 2007; Zuidhoek, Kappers, Noordzij, Van der Lubbe, & Postma, 2004a), or providing visual cues (Newport et al., 2002; Van Mier, 2013; Volcic et al., 2008; Zuidhoek, Visser, Bredero, & Postma, 2004b), resulted in improved performance. The same was observed when the bias of the hand-centered egocentric reference frame was reduced or eliminated (Kappers & Schakel, 2011; Van Mier, 2013).

5.1. Effect of a Delay

One of the manipulations that has been shown to improve haptic parallel matching is the introduction of a delay between the exploration of the reference bar and the parallel setting of the test bar (Zuidhoek et al., 2003; 2007). A delay of 10 sec led to improved, however still biased, performance, compared to parallel matching without a delay. The authors proposed that due to the inclusion of a delay, visual imagery of the felt orientation was stimulated resulting in a shift from an egocentric reference frame towards a more allocentric reference frame. Thus by introducing a delay, the contribution of the allocentric reference frame was increased whereas the influence of the egocentric reference frame was decreased, consequently leading to better performance on the parallelity task (Zuidhoek et al., 2003, 2007). In contrast to the above, Kaas, Van Mier and Goebel (2007a) did not show an effect of a 10 sec delay on haptic parallel matching. In their functional magnetic resonance imaging study participants performed the parallel task while lying in an MRI scanner. An important difference is that in this study an intermanual distance of only 35 cm was used, while Zuidhoek and colleagues (2003; 2007) used distances between 60 and 120 cm. Deviations at the short 35 cm distance were already very small in the condition without delay. However, brain activations observed during the delay showed involvement of different visual areas: activation in fusiform gyrus, active during the first period of the delay and parieto-occipital cortex being activated later in the delay interval (Kaas et al., 2007a), in line with the suggested visual imagery of the orientations during a delay.

Evidence pertaining to a shift from ego- to allocentric processing due to a delay also comes from studies with blind people, showing that a delay improvement on parallel setting was only found in adventitiously blind participants, not in congenitally blind participants (Postma et al., 2008; Zuidhoek et al., 2004a). It was suggested that the congenitally blind, who were blind from birth on, have limited spatial imagery abilities necessary to generate allocentric representations and therefore profit less from a delay. This is in line with results reported by Ruggiero, Ruotolo and Iachini (2012) who found that congenitally blind participants showed a difficulty in processing allocentric information regarding spatial relations in a horizontal plane compared to adventitiously blind, who became blind later in life, and blindfolded sighted participants. Results pertaining to deaf individuals showed the opposite pattern. Van Dijk, Kappers and Postma (2013) studied haptic parallelity in deaf signers, hearing sign language interpreters and hearing controls. They found that the former had significantly smaller deviations after a 2 and 10 sec delay than both hearing groups, whose deviations were not significantly different. According to the authors, these results suggest that deaf individuals might be better in processing allocentric spatial information, most likely because of a stronger reliance on visual spatial processing and/or superior visuospatial capacity.

Although not directly comparable to the above-mentioned delays, unimanual performance resulted in quantitatively smaller deviations than bimanual performance (Kappers, 1999; Kappers, 2002). In the former the same hand explored the orientation of the reference bar and reproduced this orientation on the test bar, while in the latter both hands were used handling both bars simultaneously. It was suggested that the memory component involved in the unimanual condition might have stimulated the use of a more allocentric reference frame, by means of visual imagery or cognitive processing.

5.2. Influence of (Non-) Informative Visual Information

Haptic parallelity judgments have also been affected by the provision of vision, informative as well as non-informative, resulting in smaller deviations. Non-informative vision refers to the fact that, although participants were provided with visual information about their environment, this information was not directly relevant to the task itself. Performance on the haptic parallelity task in which participants were blindfolded, was compared to performance on the parallelity task in which they were provided with non-informative vision. In the latter condition, the set-up and the hands of the participants were blocked from their view but they were able to freely look around. A significant reduction in deviations in the parallelity task was found in the condition with non-informative vision (Newport et al., 2002; Volcic et al., 2008; Zuidhoek et al., 2004b). The results of these studies imply that vision, even although non-informative, stimulated the use of an allocentric reference frame. However, the bias of the egocentric reference frame could not be cancelled out completely, since systematic deviations were still obtained and improvements on the parallelity task were only reflecting a small percentage of the total deviation. Non-informative vision has also been shown to improve the spatial resolution of touch in participants (Kennett, Taylor-Clarke, & Haggard, 2001). In addition, when participants were instructed to orient their head and eyes in the direction of the reference bar in a no-vision as well as in a non-informative vision condition, smaller deviations were observed in both conditions compared to directing head and eyes straight ahead (Zuidhoek, et al., 2004b). The authors hypothesized that this orienting behavior might have increased visual imagery and/or attentional resources, modifying the initial egocentric representation into a more allocentric representation resulting in improved perception of the haptically perceived orientation of the reference bar. However, another explanation might be that the improvement is due to the fact that when the head is turned towards the bar that is explored, proprioceptive and haptic input are thought to be remapped in a more allocentric reference frame, as suggested by results reported by Lawson, Boylan and Edwards (2014).

A reduction in deviations was even found when participants received interfering visual information in the parallelity task. In a study by Volcic and colleagues (2008) a bar with an orientation that was different from the felt orientation, was visually presented while participants had to match the latter. Even interfering visual information seems to stimulate the use of an allocentric reference frame. In a study by Kaas et al. (2007b), in which a bar, either oriented congruently or incongruently with the orientation of the reference bar, was visually presented on a screen while the participant was simultaneously performing a haptic parallelity task, no beneficial effect of visual information was found. A notable difference with the above mentioned studies is that in the study by Kaas and colleagues (2007b) participants could only see the screen through a black tube, without any reference to the edges of the screen or any other external cues. This suggests that it is the information obtained from the surrounding environment that induces the use of an allocentric reference frame, not vision per se.

To study the effect of informative vision, Van Mier (2013) conducted a study including a condition in which participants had full view of the test bar and their matching hand, while the reference bar and exploring hand were blocked from their view. Compared to a reduction in deviations of 9% (Volcic et al., 2008; Zuidhoek et al., 2004) to 17% (Newport et al., 2002) as a result of non-informative vision, deviations in the so-called visual haptic parallelity task of Van Mier (2013) were almost half the size of the deviations observed in the standard haptic parallelity task. It was suggested that being able to make use of external visual cues in the visual haptic parallelity task, like the sides of the table and/or the sides of the metal plate with the protractor and bar, stimulated the use of an allocentric reference frame even more than non-informative vision.

5.3. Reduction or Elimination of the Egocentric Bias of the Hand(S)

Improved parallelity matching has been reported in conditions where the egocentric bias of the hands was decreased. Van Mier (2013) showed that when the egocentric bias of the hands was reduced in the parallelity task, deviations were considerably smaller (up to 70%). In one of the conditions of this study, the visual haptic parallelity drawing condition, participants were instructed to parallel the orientation of the reference bar by drawing instead of setting the orientation of the test bar. They had full view of their drawing hand, but the reference bar and consequently the hand that explored this bar, were blocked from their view. Because participants had to draw lines with a length of at least 20 cm, the drawing movements were directed by the arm/shoulder (Dounskaia, Goble, & Wang, 2011), compared to movements that were guided by the hand when participants paralleled the orientation of the reference bar using the test bar. In the haptic parallelity condition participants use the whole hand to position the bar in the perceived orientation and most likely try to align both hands. In the visual haptic parallelity drawing condition the hand is mainly used to hold the pen to draw and parallel the orientation of the reference bar, while the drawing movement is made from the arm/shoulder. The improvement was not just due to the fact that subjects were able to see their drawing hand. In the same study participants explored the orientation of the reference bar, with both hand and bar being out of view, while they had full view of their matching hand and the test bar. In this visual haptic parallelity condition, deviations were almost half the size of those in the regular haptic parallelity task. However, deviations in the visual haptic parallelity and the visual haptic parallelity drawing condition differed significantly, with an additional significant improvement in the drawing condition. Although participants had full view of their ‘matching’ hand in both conditions, in the visual haptic parallelity task participants touched the entire length of the bars with their full hands in order to perceive and parallel the orientation. The improved performance when drawing the orientation must therefore be due to the reduced bias of the hand and the use of the arm/shoulder.

Kappers and Schakel (2011) included a visual condition in their study in which the use of the hands was completely eliminated. Participants did not rotate the test bar themselves, but they had to instruct the experimenter how to rotate the test bar in order to make it parallel to the reference bar. The distance between the bars was 120 cm. Compared to the haptic condition deviations in the visual condition were significantly smaller, being only 25% of those in the haptic condition. Performance, however, was not veridical, and still suggests an egocentric bias in the visual condition. In this condition, participants most likely used an eye-centered reference frame, being less biased then the hand centered-reference frame in haptic parallel setting.

6. Gender Differences

A consistent finding in haptic parallelity matching is the observation that men outperform women in this task. In her study including 68 participants, 34 males and 34 females, Kappers (2003) found that women had on average deviations that were 12.7° larger than those of men. It might be suggested that these gender differences in Kappers’ study were due to differences in education or job experience. With 40% of the female participants having administrative jobs and 60% being physicists, only 3% of the male participants had an administrative job while 97% were either physicists or technicians. However, a direct comparison between female and male physicists showed that the latter had deviations that were 7° smaller than those of their female colleagues, suggesting that the gender difference was not only dependent on education and/or job experience. This gender related advantage for men regarding haptic parallelity matching has since then been replicated by others in the mid-horizontal plane (Kaas & Van Mier, 2006; Kappers, 2007; Van Mier, 2013; Volcic et al., 2008; Zuidhoek et al., 2007) and frontoparallel plane (Hermens et al., 2006).

The abovementioned gender difference in deviations might be explained by different contributions of the egocentric reference frame in women than in men when performing a parallelity task. Kappers (2007) found that males had smaller egocentric weighting factors than females, and suggested that women might be more egocentrically oriented than men. Based on the fact that the inclusion of a delay of 10 sec showed an improvement that was similar in men and women, Zuidhoek et al. (2007) proposed that men not necessarily rely more on an allocentric reference frame, but that they are better than women at overcoming egocentric biases when performing haptic tasks. In the same study they asked participants to rotate a bar to match a clock time that was verbally presented to them by the experimenter and found no significant differences related to gender. According to the authors, the act of rotating a bar seems to be less biased by an egocentric (hand) reference frame. No information was provided regarding the way participants performed this task. However, it is very plausible that participants did not use their whole hand to rotate the bar, but their fingers, resulting in a reduction of the bias of the hand. On the other hand, when participants were instructed to report the orientation of a bar as a clock time, significant gender differences were found. In this so-called perception task, participants pressed the hand on the bar sometimes followed by a hand movement over the bar, most likely using their whole hand to explore and feel the orientation of the bar, introducing an egocentric bias by the hand. This idea is supported by results of Van Mier (2013), who found that providing visual information resulted in improved performance that was similar in both genders. Although both males and females were able to use the allocentric cues provided by the visual information of (the set-up of) the test bar, performance of the female participants was significantly worse than of the male participants. In this condition participants touched the entire length of the bars with their full hands in order to perceive and replicate the orientations, which most likely biased the performance of the women more than of the men. The abovementioned results suggest that both genders profit to the same extent when allocentric processing is stimulated. The finding that women still had larger deviations than men can be ascribed to the fact that women have more problems overcoming the egocentric bias of the hand.

If the latter is indeed the case, differences in performance between women and men should not significantly differ in conditions where the egocentric bias is absent or minimized. In studies that reported non-significant gender differences in parallelity matching, this can most likely be attributed to the above. In one of the studies, Kappers and Schakel (2011) compared gender related performance between a haptic and a visual parallelity condition. They found significant gender related differences in the haptic condition, but not in the visual condition. In the latter, participants instructed the experimenter to orient the test bar so it would match the reference bar, instead of orienting the test bar themselves, as in the haptic condition. Therefore, the egocentric bias of the hand and arm was completely eliminated in the visual condition.

Differences between male and female participants were also not significant in the study of Kappers and Liefers (2012). As stated above, in this study participants explored and matched the orientation of the reference and test bar at the same location horizontally with a slight difference vertically. The authors assumed that the non-significant gender difference was due to the limited number of participants (6 males and 6 females) in their study. However, one might speculate that the lack of a gender difference in their study is due to the fact that the distance between the hands was zero. As has been described above, for a more egocentrically oriented participant, increasing the horizontal distance between the bars will affect the orientation of the hands more than for a participant that is more allocentrically oriented. So in conditions where there is a horizontal distance between both hands, a more egocentrically oriented participant will have larger deviations. However, when the hands perform the task at the same position in horizontal space, as was the case in the study by Kappers and Liefers (2012), no difference would be expected between more ego- and allocentrically oriented participants. The absence of a gender effect in this study is consistent with the abovementioned idea.

When the egocentric bias of the hands was minimized, as in the study by Van Mier (2013), deviations between female and male participants did not differ significantly. As reported above, in the visual haptic parallelity drawing condition participants had to draw the matched orientation. Because the drawing movement was guided by the arm/shoulder, and the influence of the hand-centered egocentric reference frame was reduced, the latter did not bias performance of the female participants as was the case in the haptic parallelity and visual haptic parallelity conditions. Only in the latter conditions, performance of the male participants was significantly better than of the female participants.

Additionally, no differences between women and men were found in the haptic mirror task, where the use of an egocentric hand reference frame is beneficial (Kaas & Van Mier, 2006; Van Mier, 2013). Even when the distance between the bars was twice the length of the arm, both genders performed equally. As stated before, even when women perform this task egocentric and men allocentric, in the mirror task this would result in the same orientation, which was indeed the case.

Taken together, the findings with respect to gender differences in the parallelity task corroborate the claim that women profit from the use of an allocentric reference frame in parallel setting to the same extent as men, but might be less efficient in overcoming the egocentric bias of the hand.

7. Conclusion

Research performed during the last 15 years has shown that haptically perceived parallel settings deviate from veridicality. The reported deviations support the view that an intermediate frame of reference modulates the haptic perception of parallelity. The biases found in haptic parallel matching are consistent with the idea that ego- and allocentric reference frames play complementary roles. The systematic direction of the deviations suggests that the nature of the egocentric reference frame is most likely centered on the hand. The extent to which each frame contributes has been found to depend on factors such as the horizontal distance between the hands; the orientation of the bars; training and feedback; task condition and instruction; gender of the participant; inclusion of a delay; provision of (non)informative cues; and reduction of the egocentric bias. The reported findings strengthen the idea of a reference frame based model in the haptic perception of parallelity.

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