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Effects of visual information regarding allocentric processing in haptic parallelity matching

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ABSTRACT

Research has revealed that haptic perception of parallelity deviates from physical reality. Large and systematic deviations have been found in haptic parallelity matching most likely due to the influence of the hand-centered egocentric reference frame. Providing information that increases the influence of allocentric processing has been shown to improve performance on haptic matching. In this study allocentric processing was stimulated by providing informative vision in haptic matching tasks that were performed using hand- and arm-centered reference frames.

Twenty blindfolded participants (ten men, ten women) explored the orientation of a reference bar with the non-dominant hand and subsequently matched (task HP) or mirrored (task HM) its orientation on a test bar with the dominant hand. Visual information was provided by means of informative vision with participants having full view of the test bar, while the reference bar was blocked from their view (task VHP). To decrease the egocentric bias of the hands, participants also performed a visual haptic parallelity drawing task (task VHPD) using an arm-centered reference frame, by drawing the orientation of the reference bar. In all tasks, the distance between and orientation of the bars were manipulated.

A significant effect of task was found; performance improved from task HP, to VHP to VHPD, and HM. Significant effects of distance were found in the first three tasks, whereas orientation and gender effects were only significant in tasks HP and VHP. The results showed that stimulating allocentric processing by means of informative vision and reducing the egocentric bias by using an arm-centered reference frame led to most accurate performance on parallelity matching.

1. Introduction

When we want to locate an object in our working space, we can use the input of several sensory modalities. Visual and haptic, and in some cases even auditory, information of the object might help us to establish the location of the object in such a way that we are able to reach for it, grasp it, use it and/or manipulate it. In this case we define the location of the object with respect to our own body, which is called egocentric processing. On the other hand, when the location of an object is defined in relation to another object this is referred to as allocentric processing. In the former we use an egocentric reference frame, in the latter an allocentric frame to specify the location or orientation of the object (Klatzky, 1998). Especially when visual input is not available, the haptic sense plays an important role in providing information about the space around us. Contrary to what one would expect, our perception of haptic space is not veridical.

Pioneering research by Blumenfeld (1937) and Brambring (1976) had already shown that space in the haptic domain is distorted and that haptic distance estimates are non Euclidean. The representation of orientations in haptic space has been of interest to several researchers, especially the judgment of haptic spatial relations which has been studied in more details by Kappers (Kappers, 1999; Kappers & Koenderink, 1999). By using a haptic parallelity task, in which blindfolded subjects had to match the orientation of a test bar in such a way that it felt parallel to the orientation of a reference bar, it was shown that what participants feel as being parallel deviates largely from what is physically parallel. Deviations were not only large they were also systematically directed in the (natural) orientation of the hand and have been observed in haptic parallelity tasks performed in the (mid)horizontal plane (Kaas & Van Mier, 2006; Kappers, 1999, 2004; Kappers & Koenderink, 1999; Newport, Rabb, & Jackson, 2002; Zuidhoek, Kappers, Van der Lubbe, & Postma, 2003), the midsagittal plane (Kappers, 2002), the frontoparallel plane (Hermens, Kappers, & Gielen, 2006; Volcic, Kappers, & Koenderink, 2007), the three-dimensional plane (Volcic & Kappers, 2008) and in rear peripersonal space (Fernández-Díaz & Travieso, 2011).

The observation that deviations in the haptic parallelity task are large and systematic implies that participants do not (only) use an allocentric reference frame, because the use of such a frame would result in veridical performance, with both bars being physically parallel. On the other hand the deviations are smaller than expected when (only) an egocentric hand

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reference frame would be favored. Therefore, Kappers proposed a frame of reference intermediate to an allocentric frame anchored to external space and an egocentric frame centered on the body, with the hand as most likely candidate (Kappers, 2003). The deviations observed in haptic parallel matching seem to be the result of the use of a reference frame that is a weighted average of egocentric and allocentric reference 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; Volcic, Van Rheede, Postma, & Kappers, 2008; Volcic et al., 2007). Additional evidence for the biasing effect of the egocentric reference frame is the fact that the distance between the two bars has been shown to influence the magnitude of the deviations. Deviations increased 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; Zuidhoek et al., 2003), but not when the distance was changed vertically (Kappers & Koenderink, 1999). Increasing the horizontal distance between the bars not only increases the distance with respect to the body (Kaas & Van Mier, 2006), but affects also the orientation of the hands (Kappers & Viergever, 2006).

The magnitude of the deviations in the haptic parallelity task is also influenced by the orientation of the bar. It has been found that for most participants matching cardinal orientations of 0° and 90° results in smaller deviations than matching oblique orientations like 45° and 135°. This so called oblique effect reflects a generally faster and more accurate processing of stimuli aligned with vertical and horizontal orientations than with oblique orientations (e.g. Gentaz & Hatwell, 1995; Hermens et al., 2006; Kaas & Van Mier, 2006; Kappers, 1999, 2004; Kappers & Viergever, 2006; Lechelt & Verenka, 1980; Volcic et al., 2007).

Additional evidence supporting the idea of an intermediate reference frame comes from studies in which a delay was introduced between the exploration of the reference bar and the parallel setting of the test bar (Zuidhoek, Kappers, & Postma, 2007; Zuidhoek et al., 2003). Introducing a delay of 10 seconds led to improved, but still biased, performance. It was suggested that this improvement was caused by a shift from an egocentric frame towards a more allocentric reference frame. The authors proposed that the inclusion of a delay stimulates the visual imagery of the felt orientation. Another manipulation leading to reduced deviations was the provision of non-informative vision. In these studies participants performed the parallelity task under two conditions. In one condition they were blindfolded, in the other condition they were allowed to look around while their hands and the set-up were blocked from their view with the visual information not being directly relevant to the task itself. Results showed that non-informative vision led to a significant reduction in deviations in the parallelity task (Newport et al., 2002; Volcic et al., 2008; Zuidhoek, Visser, Bredero, & Postma, 2004). Volcic et al. (2008) additionally showed that even providing interfering visual information, by presenting visually a bar with an orientation that was different from the felt orientation reduced the deviations. It was suggested that vision, even when it was non-informative or interfered, stimulated the use of an allocentric reference frame.

The magnitude of the deviations has been found to be gender-dependent, meaning that men and women perform differently in this task. Kappers (2003) found that the deviations of women in the parallelity task were on average 12.7° larger than those of men. This gender related difference in haptic parallelity matching has since been replicated (Kaas & Van Mier, 2006; Kappers, 2007; Volcic et al., 2008; Zuidhoek et al., 2007). In line with the above, the gender difference in deviations might be explained by a different contribution of the egocentric reference frame in women than in men when performing a parallelity task. Kappers (2007) proposed that women might be more egocentrically oriented than men. It has also been suggested that men not necessarily rely more on an allocentric reference frame, but are only better at overcoming egocentric biases when performing haptic tasks than women (Zuidhoek et al., 2007).

When referring to egocentric reference frames, it is important to specify on which body part(s) the reference frame is centered. Evidence for a hand-centered reference frame in the parallelity task was shown in a study by Kappers and Viergever (2006), in which participants performed the haptic parallelity task under different conditions having their hands either oriented straight ahead, rotated to the left, to the right, outwards or inwards. The size of the deviations depended strongly on the relative orientation of the hands in a way predicted by a predominantly hand-centered egocentric frame of reference, although an additional but much smaller influence of the body-centered frame could not be excluded. Additional support for the former was found in a three-dimensional parallelity task, in which Volcic and Kappers (2008) showed that the deviations were best described by a hand-centered weighted average model that assumes a weighted egocentric biasing effect of the hand on the allocentric frame of reference. Studies focusing on the haptic perception in a mirror task in the mid-horizontal plane (Fernández-Díaz & Travieso, 2011; Kaas & Van Mier, 2006; Kaas, Van Mier, & Goebel, 2007; Kaas, Van Mier, Lataster, Fingal, & Sack, 2007; Kappers, 2004, 2007), in which the test bar has to be turned until the reference bar and the test bar form each other's mirror image, showed that the mirror task led to small and random deviations, and thus could be performed almost veridical (Kaas & Van Mier, 2006; Kappers, 2004). If a task can be performed veridical, this means that the average settings of a participant correspond to the settings one would expect if haptic space was Euclidean (Kappers & Koenderink, 1999). Thus in contrast to the parallelity task for which large and systematic deviations were found, the mirror task led to only small and random deviations. These differences in size of deviations might most likely be explained by the reference frame being used by the participants. In the mirror task using an egocentric reference frame by mirroring the setting of the hands to each other, leads to the same, more or less veridical, performance as the use of an allocentric reference frame (Kappers, 2004, 2007). If women are indeed more egocentrically oriented than men as Kappers (2007) suggested, no gender differences would be expected in the mirror task. Kaas and Van Mier (2006) have already shown that this is indeed the case when a short distance (up to 60 cm) between the hands was used. The present experiment will test if this is also the case when the distance between the hands is increased to 120 cm.

Making a test bar parallel to a reference bar at a 90° orientation (vertical orientation of the bar) involves the same setting of the bar and positioning of the hands as mirroring this orientation, and therefore one would expect that in both conditions the same deviations would be found. However, this was not the case. Making the bars parallel at the abovementioned orientation resulted in larger deviations than mirroring the bars (Fernández-Díaz & Travieso, 2011; Kaas & Van Mier, 2006; Kappers, 2004). Performance clearly depended on the experimental task instruction, and as Kaas and Van Mier (2006) suggest, this indicates that the use of the reference frames might also vary intra-individually.

The goal of the present study was to further qualify the effect of informative vision on haptic matching performance and the influence of minimizing the egocentric bias of the exploring hand. Next to the standard haptic parallelity and mirror tasks, we included informative vision in the parallelity task by providing participants with full view of the test bar and their matching hand while the reference bar was blocked from their view (visual haptic parallelity task). We hypothesize that this will result in a shift to more allocentric processing resulting in smaller deviations for this task. To decrease the influence of the hand we added a condition in which participants were instructed to match the orientation of the reference bar by drawing the parallel orientation. In this condition the hand was only used to hold the pencil but the drawing movement was guided by the arm/shoulder (visual haptic parallelity drawing task). Again participants had full view of their drawing hand but the reference bar was blocked from their view. If the egocentric reference frame used in the parallelity task is indeed hand-centered, we expect significantly smaller deviations in this condition in which matching is much less biased by the orientation of the hand. Additionally, we assume smaller differences in deviations between men and women in the parallelity drawing task.

The abovementioned effects of distance, orientation and gender have not been observed in the haptic mirror task but were only reported for the haptic parallelity task and are hypothesized to be caused by the biasing effect of the hand-centered egocentric reference frame. If this is indeed the case, we expect that having participants perform the matching part of the experiment in an arm/shoulder-centered reference frame would cancel the bias of the hand and the abovementioned effects, as is the case in the mirror task. Providing informative visual feedback is expected to decrease deviations but due to the bias of the hand in the matching phase, we assume that these factors will still influence the size of the deviations in the visual haptic task.

2. Method

2.1. Participants

Twenty adults with a mean age of 39.8 years (SD = 19.6, range 22–85 years) took part in this study, ten males and ten females with a mean age of 39.3 years (SD = 19.7, range 22–85 years) for the men and 40.3 years (SD = 19.4, range 22–82 years) for the women. Handedness of the participants was assessed by a Dutch translation of the hand preference questionnaire of Annett (Annett, 2004). One participant showed left-handed dominance, the other participants were right-handed. Participants had normal or corrected-to-normal vision and were remunerated for their participation. They were naive with respect to the experimental setup and objectives and did not receive feedback on their performance. Informed consent was obtained prior to the experiment. The study was approved by the local ethics committee and was performed in accordance with the declaration of Helsinki of 1964.

2.2. Apparatus

The setup consisted of two iron plates (30 × 30 cm) covered with a plastic layer on which a protractor with a diameter of 20 cm was printed (see Fig. 1). An aluminum bar with a length of 20 cm and a diameter of 1.1 cm was placed on each protractor, of which one was used as reference bar and the other as test bar. Each bar had a small pin attached in the middle which fitted in a hole in the center of the protractor. This way, the bars could be rotated 360° and could be positioned accurately in the reference orientations. Both bars had small magnets attached under it to increase the resistance against involuntary movements. The reference bar had two extra magnets attached under it to prevent participants from accidently rotating this bar while exploring its orientation. The bars had an arrow-shaped end on one side, which made it possible to accurately read the orientation of the reference and test bar with a precision of about 0.5°. An anti-slip mat was placed under each plate to avoid that the plates would move or shift during the experiment.

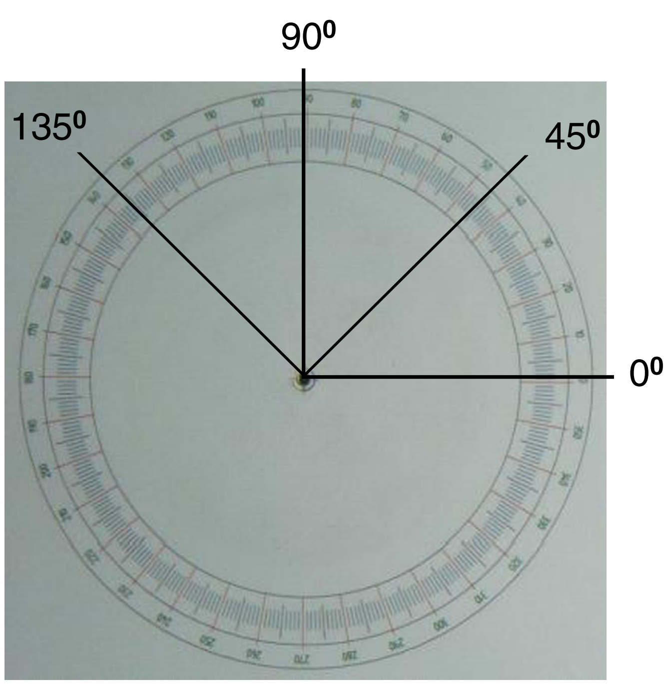

Fig. 1. The protractor and the four orientations that were used in the study.

2.3. Experimental tasks

Participants performed four different bimanual tasks, a mirror task and three parallelity tasks. In the mirror task and one of the parallelity tasks, exploration of the reference bar and matching of the test bar was performed haptically, while subjects were blindfolded. The instruction for the haptic mirror task (HM) and the haptic parallelity task (HP) was to rotate the test bar with the dominant hand in such a way that it felt as being mirrored (with respect to the midsagittal plane of the body) or parallel with respect to the reference bar, which was explored with the non-dominant hand. In the visual haptic parallelity task (VHP), the instruction was the same as in the haptic parallelity task, but participants had full view of their matching hand, while the reference bar and their exploring hand were covered. In the visual haptic parallelity drawing task (VHPD) matching was performed with the dominant hand by having participants draw a line in such a way that it was parallel to the perceived orientation of the reference bar. In this task participants had also full view of their matching hand, while the reference bar and their exploring hand were covered. Both hands were involved simultaneously during the duration of each trial.

To study the effect of horizontal distance, the distance between the pivots of the bars was either one or two times the arm length of the participant. One times the arm length will be referred to as the short distance, two times as the long distance. Arm length was derived by measuring the arm of each participant from the shoulder to the wrist, which resulted in a mean arm length of 56.7 cm (SD = 5.6). The short distance therefore resulted in a mean distance of 56.7 cm, the long distance of 113.4 cm. While men had a mean arm length of 60.1 cm (SD = 5.8), the mean arm length of the women was 53.3 cm (SD = 2.2). By taking arm length into account, each participant had to reach equally far for the bars, making it possible to compare results between participants, regardless of their arm being relatively short or long.

The effect of orientation was studied by using four reference orientations, namely 0°, 45°, 90° and 135°, of which 0° was parallel to the horizontal table edge and increasing angular values rotating in counterclockwise direction (see Fig. 1). Correct responses for the reference orientations 0°, 45°, 90° and 135° were 0°, 45°, 90° and 135° in the parallel tasks, and 180°, 135°, 90° and 45° in the mirror task, respectively. Each orientation was repeated three times.

Distance was counterbalanced between and within participants. The order of repetitions and orientations within each task was presented random and different for each participant, while the order of the four tasks was the same for all participants. They started with the haptic mirror task, followed by the visual haptic parallelity task, they then performed the haptic parallelity task and ended with the visual haptic parallelity drawing task. Because part of the data of the current participants was used as a control group in a study addressing developmental effects in children, the same fixed order as presented to the children was used. The total procedure described in this paper consisted of 96 trials (4 tasks × 2 distances × 4 orientations × 3 repetitions).

2.4. Procedure

Before the experiment started, the arm length of the participant was measured as described above and the distance between the bars was computed. Markers were taped on the table to make sure that the plates would be positioned at the same short and long distance in all tasks. Next participants were instructed on the tasks and the experiment was not started until it was clear that participants fully understood the principle of parallel and mirror and had been able to put two pens either in a mirror or a parallel position using different orientations.

The tasks were performed bimanually, meaning that both bars were touched simultaneously during the duration of each trial, or touched while drawing the orientation. Before each trial, the experimenter positioned the reference bar in one of the four predetermined orientations, and the test bar in a random orientation. Next, in the haptic mirror and haptic parallelity task in which participants were blindfolded, the experimenter placed the non-dominant hand on the reference bar and the dominant hand of the participant on the test bar. The task of the participant was to rotate the test bar in such a way that it felt mirrored or parallel with respect to the reference bar.

Participants had full view of the setup (apart from the reference bar) in the visual haptic parallelity task and the visual haptic parallelity drawing task. In the former, the test bar remained visible to the participant, while the reference bar was blocked from his or her view by a box that was placed over the plate. The side directed to the experimenter was open, making it possible for the experimenter to position the reference bar in one of the predetermined orientations without the participant being able to see what the experimenter was doing. The other side of the box had an opening covered with a piece of cloth through which the participant could place the non-dominant hand to feel the orientation of the reference bar, without seeing the bar. No specific instruction was given to the participants regarding the orientation of their head or eyes. They could freely look around and in most cases participants looked at the test bar while trying to rotate the bar in such a way that it felt as being parallel to the reference bar. The protractor on the plate with the test bar was covered with a circle that was cut out of a blank sheet of paper, to prevent participants to infer the orientation from it by reading the degrees. If the participant was satisfied with the orientation of the test bar, he or she was instructed to look away from the test bar. The experimenter then read the orientation of the test bar by lifting the circle of paper, making sure the participant could not see the protractor. In the latter, the visual haptic parallelity drawing task, the plate with the test bar was replaced by a piece of A4 paper with a circle which had the same size as the protractor and a fixed point in the middle of the circle. Each sheet was positioned on the table in such a way that a vertical 90° orientation line on the sheet would correspond with the 90° orientation of the test bar. After each trial the experimenter marked the top of the sheet and added the code of the particular trial in such a way that the orientation of the line and the deviation could be determined afterwards. The same box as in the visual haptic parallelity task was used in the parallelity drawing task to block the reference bar from the participant's view. In this task participants were instructed to reproduce the haptically explored orientation by drawing a line through the fixed middle of the circle in such a way that it was parallel to the perceived orientation of the reference bar. Before the task was performed, participants practiced drawing straight 20 cm lines in several orientations passing through the center. The hand was only used to hold the pencil. Drawing movements were guided by the arm/shoulder by having participants draw a line with a length of at least 20 cm (Dounskaia, Goble, & Wang, 2011).

Participants could use as much time as needed to perform the tasks, but they were not allowed to move their hands from one bar to the other. When the participant was satisfied with the orientation of the test bar, the experimenter read the orientation indicated by the arrow-shaped end, and wrote it down without giving any feedback about the correctness to the participant. The orientations of the drawn lines in the parallelity drawing task were analyzed offline by overlaying the circle with a protractor, using the abovementioned mark to establish the top of the sheet.

2.5. Data analyses

The dependent variable was the smallest deviation between the orientation of the (right) test bar with regard to the orientation of the (left) reference bar or, in case of the mirror task, with regard to the correct mirrored orientation. Deviations counterclockwise to the orientation of the reference bar were noted as negative values, whereas deviations clockwise to the orientation were noted as positive values. To make comparison with the right-handed participants possible, for the left-handed participant this was reversed whereby deviations counterclockwise to the orientation of the reference bar were noted as positive values, whereas clockwise deviations were noted as negative values. Signed deviations were used in the analyses. The deviations were analyzed using a repeated measurement ANOVA with task (4: HM, HP, VHP and VHPD) × orientation (4: 0°, 45°, 90° and 135°) × distance (2: short and long) × repetition (3) as within-subject factors and gender (2: female and male) as between-subject factor. An additional analysis was performed in which the factor orientation was replaced by the factor obliqueness with two levels; the average deviation of 0° and 90° as cardinal orientations and of 45° and 135° as oblique orientations. To test the effect of task instruction, deviations for the 90° orientations were compared between tasks. When significant main effects were found, pair wise Bonferroni-corrected comparisons were computed to specify specific differences.

3. Results

Analysis showed that there was no significant main effect of repetition ($F(2,17) = 1.27$, $p = .31$), or any significant interactions. Mean deviations of 11.9°, 10.6° and 11.9° were found for repetition 1, 2 and 3, respectively. Therefore, deviations were averaged over the three repetitions. The statistics reported in this section result from an analysis of a 4 (task) by 2 (distance) by 4 (orientation 135°), or 2 (obliqueness) ANOVA with gender as between factor. The effect of task instruction for the 90° orientation was obtained from a 4 (task) by 2 (distance) ANOVA with gender as between factor.

Because one might argue that the mirror task is different from the other tasks in the sense that the use of an egocentric frame in this task would actually lead to veridical performance and would therefore skew the results, we performed an analysis including only the three parallelity tasks. Since this analysis showed the same statistical effects as the analysis including all four tasks, we report the data of the latter analysis.

3.1. Effect of task and distance

A highly significant main effect of task was found ($F(3,54) = 63.02$, $p < .001$). The mean deviation was 0.5° in the haptic mirror (HM) task, 12.5° in the visual haptic parallelity (VHP) task, 25.1° in the haptic parallelity (HP) task and 7.7° in the visual haptic parallelity drawing (VHPD) task. Pair wise comparisons showed that the deviations of all four tasks differed significantly from each other ($p < .05$ to $p < .001$). As expected, very small deviations were found in the haptic mirror task, while the haptic parallelity task resulted in the largest deviations. Providing informative vision in the visual haptic parallelity task resulted in a significant decrease in deviations, with an even larger decrease in the parallelity drawing task.

Distance showed a significant main effect ($F(1,18) = 61.42$, $p < .001$), with a mean deviation of 6.9° for the short distance and 16.0° for the long distance. There was also a significant interaction between task and distance ($F(3,54) = 21.48$, $p < .001$). As can be seen in Fig. 2, distance had the greatest effect in the haptic parallelity task, with a deviation of 14.6° at the short distance, and 35.6° at the long distance. As expected, this effect was smallest in the haptic mirror task, with a deviation of .2° and .8° for the short and long distance respectively. Being able to see the reference bar in the visual haptic parallelity task resulted in a deviation of 8.1° at the short distance and 17.0° at the long distance. When drawing the matched orientation, deviations of 4.9° and 10.4° were observed at the short and long distance.

3.2. Effect of orientation and obliqueness

In line with our expectations, a significant effect of orientation was found ($F(3,54) = 9.54$, $p < .001$). The orientations of 90° and 0° resulted in a mean deviation of 7.4° and 10.5°, while the 45° and 135° orientations revealed mean deviations of 13.3° and 14.7°. Pair wise comparisons revealed that the 90° orientation differed significantly from 45° ($p < .02$) and 135° ($p < .001$). Differences between orientations were not the same in all tasks (see Fig. 3), as revealed by a significant interaction between task and orientation ($F(9,162) = 5.24$, $p < .001$). While the cardinal orientations of 0° and 90° resulted in the smallest deviations in the HM, VHP, and HP tasks, the deviation for 0° in the VHPD task was much higher than for the 45° and 90° orientations and almost as high as for the 135° orientation.

Results from the separate analysis in which deviations for the cardinal (0° and 90°) and oblique orientations (45° and 135°) were averaged resulting in the variable obliqueness with 2 levels, showed a significant main effect of obliqueness ($F(1,18) = 15.29$, $p < .001$). Matching cardinal orientations yielded a mean deviation of 8.9°, oblique orientations of 14.0°. There was a significant interaction of task and obliqueness, with almost similar means for cardinal and oblique orientations in HM (0.6° and 0.4°) and VHPD (7.1° and 8.2°), while cardinal and oblique orientations resulted in quite different deviations in VHP (8.5° and 16.6°) and in HP (19.5° and 30.7°) as can be seen in Fig. 3.

3.3. Effect of gender

A significant main effect of gender was found ($F(1,18) = 5.13$, $p = .036$). Men deviated on average 8.4°, women 14.5°. However, the significant interaction of gender and task ($F(3,45) = 7.70$, $p < .001$) suggests that this difference was not the same in all tasks. Fig. 4 shows the differences between men and women in the four tasks. Analyses per task (described in more details in Section 3.5), showed that differences between men and women were only significant in the haptic and visual haptic parallelity task.

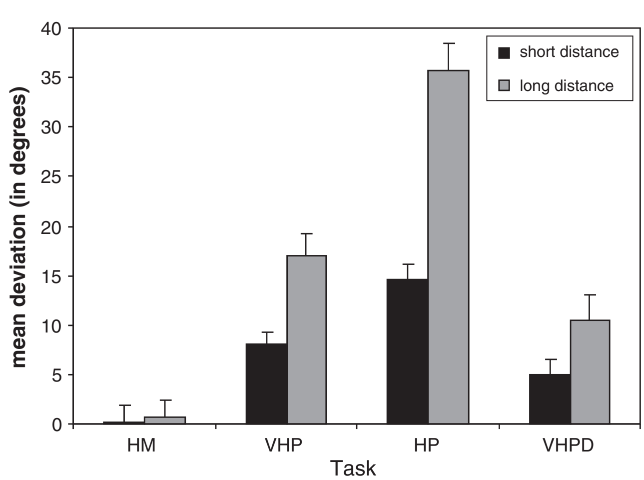

Fig. 2. Mean deviations and standard errors for the short (57 cm) and long (114 cm) mean distances in the haptic perception tasks. HM: Haptic mirror task; VHP: Visual haptic parallelity task; HP: Haptic parallelity task; VHPD: Visual haptic parallelity drawing task.

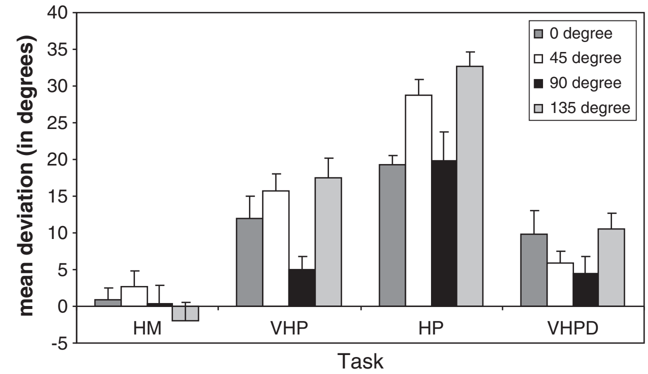

Fig. 3. Mean deviations and standard errors for the different orientations in the haptic perception tasks. HM: Haptic mirror task; VHP: Visual haptic parallelity task; HP: Haptic parallelity task; VHPD: Visual haptic parallelity drawing task.

Gender interacted also with distance ($F(1,18) = 5.31$, $p = .033$), with a much larger effect of distance for women. While for men the deviation increased from 5.3° at the short distance to 11.6° at the long distance, this increase was much larger for the female participants, from 8.6° to 20.3°.

3.4. Effect of task instruction

Because making two bars parallel or mirrored to each other requires the exact same setting of the reference bar for the 90° (vertical) orientation, one would expect no differences in deviations between the tasks. However, when comparing deviations for the 90° orientations over the four tasks, a significant effect of task was found ($F(3,54) = 18.88$, $p < .001$). A deviation of 0.3° was found in the mirror task (HM), 4.0° in the visual haptic parallelity task (VHP), 19.9° in the haptic parallelity task (HP) and 4.5° in the parallelity drawing task (VHPD) (see also Fig. 3). Pair wise comparisons revealed that deviations in the HP task were significantly larger than in the other 3 tasks (all $p < .001$). The difference between de HM and VHP task showed a trend ($p = .07$). The other comparisons were not significant.

3.5. Task specific effects

To check for specific effects of the independent variables per task, separate analyses were done for each task with distance and obliqueness as within factors and gender as between factor.

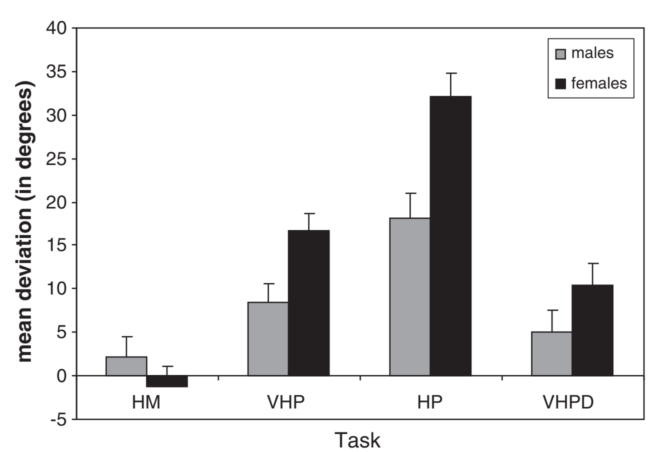

Fig. 4. Mean deviations and standard errors for males and females in the haptic perception tasks. HM: Haptic mirror task; VHP: Visual haptic parallelity task; HP: Haptic parallelity task; VHPD: Visual haptic parallelity drawing task.

3.5.1. Haptic mirror task (HM)

None of the abovementioned factors showed a significant main effect ($F(1,18) = 0.32$, $p = .58$ for distance; $F(1,18) = 1.12$, $p = .30$ for gender; $F(1,18) = 0.01$, $p = .94$ for obliqueness) nor were any significant interactions found in the haptic mirror task.

3.5.2. Haptic parallelity task (HP)

On the other hand all factors showed significant main effects in the haptic parallelity task ($F(1,18) = 72.93$, $p < .001$ for distance; $F(1,18) = 12.71$, $p < .003$ for gender; $F(1,18) = 49.77$, $p < .001$ for obliqueness). Furthermore, there was a significant interaction between gender and obliqueness ($F(1,18) = 7.31$, $p < .02$). Differences between cardinal and oblique orientations were much more pronounced in men than in women.

3.5.3. Visual haptic parallelity task (VHP)

Also in the visual haptic parallelity task significant effects were found for these factors ($F(1,18) = 20.54$, $p < .001$ for distance; $F(1,18) = 7.34$, $p < .02$ for gender; $F(1,18) = 25.93$, $p < .001$ for obliqueness). No significant interactions were found.

3.5.4. Visual haptic parallelity drawing task (VHPD)

In the parallelity drawing task only a significant effect of distance was found ($F(1,18) = 6.32$, $p < .03$), while differences due to gender and obliqueness were not significant ($F(1,18) = 2.11$, $p = .16$ for gender; $F(1,18) = 0.29$, $p = .60$ for obliqueness). No significant interaction with distance was found.

4. Discussion

The objective of the present study was to investigate the effect of informative visual information on the deviations in haptic parallelity matching. To this end, in one condition participants performed the haptic parallelity task while having full view of the test bar and in an additional condition had to draw the orientation of the bar instead of setting the bar with their hand. As predicted, including informative vision reduced the deviations significantly, while drawing the orientation of the test bar reduced the deviations even more.

In the haptic parallelity task we replicated results reported before in the literature. Large and systematic deviations were found when participants had to make the bars haptically parallel to each other. Participants deviated from veridicality and showed the same directional clockwise bias. These results are in line with numerous other studies involving the haptic parallelity task (e.g. Fernández-Díaz & Travieso, 2011; Kaas & Van Mier, 2006; Kappers, 2003; Volcic et al., 2008). Deviations were significantly larger when the distance between the hands was increased, corresponding to results found by others (Fernández-Díaz & Travieso, 2011; Kaas & Van Mier, 2006; Kappers, 1999, 2002, 2003; Zuidhoek et al., 2003) and when women performed the task compared to men, a finding that has also been reported before (Kaas & Van Mier, 2006; Kappers, 2003, 2007; Volcic et al., 2008; Zuidhoek et al., 2007). As expected an oblique effect was found with larger deviations for oblique orientations compared to cardinal orientations (Hermens et al., 2006; Kaas & Van Mier, 2006; Kappers, 2003; Kappers & Viergever, 2006; Volcic et al., 2007).

With regard to the mirror task, our results are also in line with earlier studies. Mirroring the bars resulted in small and random deviations as found by others (Fernández-Díaz & Travieso, 2011; Kaas & Van Mier, 2006; Kaas, Van Mier and Goebel, 2007, Kaas, Van Mier, Lataster, et al., 2007; Kappers, 2004, 2007). Additionally, no significant effects of distance, orientation and gender were found in this task, consistent with results reported by Kaas and Van Mier (2006). We showed that increasing the distance between the hands from around 60 to 120 cm did not lead to significantly larger deviations or significant differences between men and women at the larger distance, most likely suggesting that men and women perform this task in the same (egocentric) reference frame.

4.1. Adding informative vision

The present study extends the abovementioned findings by demonstrating that providing informative vision in the parallelity task resulted in a reduction of around 50% of the deviations, compared to those in the pure haptic version of the task. Consistent with studies that showed that even providing non-informative or interfering vision resulted in smaller deviations (Newport et al., 2002; Volcic et al., 2008; Zuidhoek et al., 2004), an increase in performance was anticipated. While adding non-informative vision showed improvements of about 9% (Volcic et al., 2008; Zuidhoek et al., 2004) to 17% (Newport et al., 2002), providing informative visual cues improved performance up to 50% in our study. One might even have expected that due to visualization of the test bar and matching hand participants would have performed even more veridical, arguing that they would be able to compensate for the biased influence of the matching hand. Studies in which participants had to estimate or match clock times (Hermens et al., 2006; Zuidhoek, Kappers, & Postma, 2005) showed smaller deviations in those conditions, suggesting that participants are indeed able to compensate. However, in the current study participants only saw the test bar, not the reference bar. As Hermens et al. (2006) state, the deviations in the parallelity task most likely originate from the transfer of the reference orientation to the position of the matching bar, which also played a role in our task. When just naming or producing an orientation or a clock time, no transfer is needed. While the first two stages of the matching task, namely the perception of the orientation and the transfer of the perceived orientation to the matching orientation, are the same in the haptic and visual haptic task, the third stage, the production of the transferred orientation, is different in both tasks. Whereas participants most likely use an egocentric reference frame that is mainly biased on what the hand feels in the haptic parallelity task, in the visual haptic parallelity task they probably shifted to a more allocentric reference frame making use of external visual cues like the sides of the metal plate with the protractor, the sides of the table etc. Millar and Al-Attar (2004) found that adding external frame cues in a tactile street map that contained raised lines for streets forming an irregular route, resulted in performance being twice as accurate as without the frame. In that condition participants concomitantly scanned the raised-line frame surrounding the map. Furthermore, Kappers, Postma, and Viergever (2008) have shown that only when participants were given visual feedback about the deviations in the parallelity task in a training phase, performance on the haptic parallelity task improved. In our study participants did not receive feedback on their performance. One has to keep in mind that deviations from veridicality have also been found in visual parallelity tasks (Cuijpers, Kappers, & Koenderink, 2003) and in a visual parallelity task in which a reference and test bar were used resembling the current parallelity task (Kappers & Schakel, 2011, see also Section 4.2). The finding of complete veridical performance in the visual haptic parallelity task was therefore not expected.

As assumed, the effects of distance, obliqueness and gender were less pronounced in the visual haptic task than in the haptic task. However, these effects were still significant, suggesting that performance was only partly compensated by the use of the allocentric reference frame and that the egocentric bias of the hand could not be completely eliminated.

To summarize, the data regarding the visual haptic task showed that informative visual information improved parallel setting and provide additional support for the intermediate frame of reference hypothesis in haptic spatial matching. As was the case in studies introducing a delay between exploration and matching (Zuidhoek et al., 2003, 2007) and using non-informative vision (Newport et al., 2002; Volcic et al., 2008; Zuidhoek et al., 2004), manipulating the task in such a way that participants could employ an allocentric reference frame, resulted in smaller deviations.

4.2. Parallelity drawing

Asking participants to draw the orientation of the test bar, instead of matching it with their hand, reduced the deviations even further, up to 70%. As stated above, in the visual haptic parallelity task, being able to see the test bar and their matching hand makes that participants are to a certain extent able to compensate for the biasing influence of the hands. When reducing the latter by drawing the orientation from the arm/shoulder, deviations decreased even further, but were still larger than in the haptic mirror task. Although drawing the orientation of the reference bar also involves the hand there are clear differences. When matching the test bar to the reference bar, the (whole) hand is used to position the bar in the perceived orientation, with participants trying to align their hands. When drawing the orientation, the hand is mainly used to hold the pencil while the drawing movement is executed from the arm/shoulder. With regard to the fact that performance in the parallelity drawing task still deviated from being veridical, the same as mentioned above for the visual haptic task applies here. Because the haptic encoding and transfer phases of the orientation are most likely done egocentrically, it is only the production phase that due to vision can be done more allocentrically. As was the case in the visual haptic task, participants could make use of the external visual cues such as the sides of the paper and the table etc. Furthermore, even in a visual parallelity task where both the reference and test bar were visible and not the participant but the experimenter had to rotate the test bar (instructed by the participant), systematic deviations from veridicality were found (Kappers & Schakel, 2011). This suggests that visual space also shows egocentric distortions. The mean deviation in their visual condition (with a distance of 120 cm between the bars) was 14.6°, being even larger than the deviations in our parallelity drawing task for the comparable long distance (being 10.4°). In contrast to our study, where participants had full view of the setup and surroundings, in Kappers and Schakel's study visual information from the environment was minimal. The experimental room was painted black, the protractor and plate were covered by a circular sheet of black cardboard, and participants only saw the arm and hand of the experimenter. The use of visual cues was therefore minimized, which might explain the difference in the magnitude of the deviations between both studies. Millar and Al-Attar (2005) have shown that touch with diffuse light perception, which eliminated all spatial cues, had no beneficial effect on a tactile landmark task. So, when visual stimulation adds minimal cues related to spatial aspects of the task, less improvement is to be expected.

Another factor that might have contributed additionally to better performance in the visual and drawing parallelity task may be related to orienting behavior of head and eyes. In a study of Zuidhoek et al. (2004), improvement in performance was found when participants oriented head and eyes towards the orientation of the reference bar (in both a no-vision and a non-informative vision condition). They hypothesized that orienting behavior might improve perception of the haptically perceived orientation of the reference bar as a result of increased visual imagery. We observed that at the beginning of the trial, participants were looking at the direction of the box that covered the reference bar when they could see the set-up in the VHP and VHPD task. This most likely resulted in more orienting behavior towards the reference bar than in the blindfolded condition of the haptic parallelity task, where this was not observed. However, because we did not specifically focus on the position of the head and/or direction of the eyes in the parallelity tasks, we can only speculate.

It is possible that differences between performance in the visual haptic and the parallelity drawing task might be related to differences in the execution of the task. Whereas in the former participants often adjusted the test bar several times before setting the final orientation, in the latter no adjustments were made. In all cases only one line was drawn and the lines were straight. Because there was no time limit or speed instruction regarding drawing the orientation, participants had no problem producing a straight line that passed through the center. This constraint in the parallelity drawing task might have additionally stimulated the use of an allocentric reference frame resulting in smaller deviations.

As assumed, we found no significant effect of obliqueness and gender, although distance significantly affected the deviations. Apparently, the position of the arm/shoulder affects drawing at short and long distances, while this is not the case when drawing cardinal versus oblique orientations. In the parallelity drawing task, deviations were larger for 0° and 135°, than for 45° and 90°. This is most likely due to biomechanical factors that play a role in drawing movements. Research regarding line drawing and stroke production has shown that right-handers show directionality preferences when using the dominant hand for orientations comparable to our 90° and 45° orientations (Dounskaia, Van Gemmert, & Stelmach, 2000; Van Sommers, 1984; Wang, Johnson, Sainsburg, & Dounskaia, 2012). It was found that the variability was much higher when drawing lines oriented at 0° and 135° compared to 45° and 90° orientations (Danna, Athènes, & Zanone, 2011; Dounskaia, Ketcham, & Stelmach, 2002; Dounskaia et al., 2000).

In sum, decreasing the bias of the hands by using the arm/shoulder to draw the orientation resulted in smaller deviations. These results support the idea of the utilization of a mainly hand-centered egocentric reference frame in the haptic parallelity task as suggested by studies involving different orientations of the hands (Kappers & Viergever, 2006), or setting bars parallel in three dimensions (Volcic & Kappers, 2008).

4.3. Gender differences

We only found significant differences between males and females in the haptic and visual haptic parallelity tasks. Differences in the former task are in accordance with those reported by others (Kaas & Van Mier, 2006; Kappers, 2003, 2007; Volcic et al., 2008; Zuidhoek et al., 2007). The observed gender differences in our study cannot be due to physical differences related to arm length because we adjusted for the latter. Although it is often argued that males perform better in spatial tasks because they more often use allocentric processing, research by Van Gerven, Schneider, Wuitchik, and Skelton (2012) showed that this is not the case. In their study, male and female participants had to navigate in an "ambiguous" virtual Morris water maze that permitted participants to choose and use either an allocentric or an egocentric strategy with equal efficiency. At the end of training, a novel probe trial revealed that women used allocentric processing to the same extent as men, if not more, but that the latter were better and more efficient at employing allocentric strategies. This might explain the fact that we still found gender differences in the visual haptic parallelity task. While both males and females were able to use allocentric processing due to the visual information of the test bar, females still performed worse than males because they most likely have more problems overcoming the egocentric bias of the hand when matching the orientation. This idea is supported by the results of Zuidhoek et al. (2007) who found that introducing a delay of 10 seconds showed an improvement that was similar in both genders. A direct comparison of the haptic and visual haptic task in the current study showed an insignificant interaction of gender and task which is in line with the gender effect in the delay condition of Zuidhoek et al. (2007). This suggests that both females and males profit to the same extent from the use of an allocentric reference frame in the visual haptic task. Only when the egocentric bias of the hand was eliminated, the gender effect was absent, as was found in the parallelity drawing task. This result is in line with the findings by Zuidhoek et al. (2007) who found no gender differences when participants had to rotate a bar to match a clock time. They suggested that the act of rotating is less biased by an egocentric (hand) reference frame. The authors do not provide information on the way in which participants held their hand in this action task, but it is likely that participants used their fingers instead of their whole hand to orientate the bar, thereby reducing the bias of the hand. This would explain the fact that gender differences were found in their perception task, in which participants most likely used their whole hand to feel the orientation of the bar. In our study participants touched the entire length of the bars with their full hands in order to perceive and replicate an orientation in the haptic and visual haptic parallelity tasks. Our data from the parallelity drawing task fit with this line of thought. Using the arm/shoulder by drawing the orientation eliminates the bias of the hand to a certain extent. When the use of an egocentric hand reference frame is beneficial, as in the haptic mirror task, females and males also perform similar, corresponding to results reported by Kaas and Van Mier (2006). Interestingly, Kappers and Schakel (2011) found gender related differences in their haptic parallelity condition, but not in the visual parallelity condition. In the latter, participants did not orient the test bar themselves but instructed the experimenter. The egocentric bias of the hand or arm/shoulder was therefore completely eliminated. If women indeed are less successful in overcoming the egocentric bias of the hand, eliminating the bias or use of the hand, should also eliminate differences between the genders, which was indeed the case in our haptic parallelity drawing task and the visual parallelity condition in the study of Kappers and Schakel (2011).

To sum up, the results with respect to gender differences in the parallelity task support the suggestion that women profit to the same extent from the use of an allocentric reference frame in parallel setting, but are most likely less efficient in overcoming the egocentric bias of the hand.

4.4. Effect of task instruction

A significant effect of task was expected with superior performance for the mirror task compared to the parallel tasks, as has been reported before (Fernández-Díaz & Travieso, 2011; Kaas & Van Mier, 2006; Kappers, 2004; Newport et al., 2002). However, because the exact same setting of the reference bar and therefore the same positioning of the hands is required for the 90° orientation in all four tasks, one would assume that the deviations would be comparable. This was however, not the case. Especially in the haptic parallelity task, deviations for this orientation were large, almost 20°, this in contrast to the deviations in the other tasks, ranging from 0.3° to 4.5°. Significant differences between haptic mirror and parallel tasks for the 90° orientation have also been reported by Kaas and Van Mier (2006). Although they did not statistically compare mirror and parallel matching at 90°, also Kappers (2004) and Fernández-Díaz and Travieso (2011) found large differences between both tasks at this orientation. It is clear that task instruction had an effect on how participants performed the task, resulting in rather large systematic clockwise deviations in the haptic parallelity task. Being able to see the matching bar had a large effect on the deviations for the vertical 90° orientation in the visual haptic parallelity task. Deviations were comparable to those in the parallelity drawing task as can be seen in Fig. 3. For this orientation the external visual cues improved performance considerably resulting in only a small deviation. We speculate that this orientation benefits most from the external visual cues. Participants are able to use the spatial aspects provided by the sides of the metal plate and/or table. As Kaas and Van Mier (2006) suggested, task effects most likely reflect differences in cognitive-computational processing due to task-dependent weighting of the contributions of the ego- and allocentric coordinate frames. Stimulating the use of an allocentric reference frame in the VHP and VHPD tasks shifts the contribution more towards the latter.

Although matching the 0° orientation can also be performed similar in the mirror and parallelity task by positioning the hands in the same orientation, most participants positioned their hands mirrored in the mirror task (with both thumbs towards or away from the body), and used a parallel positioning of the hands in the parallel task. A direct comparison for the 0° orientation between the tasks was therefore not performed, because one cannot rule out that task effects might still be related to differences in motor execution.

4.5. Conclusion

In conclusion, the results from the current study provide additional supporting evidence that ego- and allocentric reference frames play complementary roles in haptic spatial matching. The contribution of the frames apparently depends on the orientation of the bars, task condition and instruction, as well as gender of the participant. Providing informative visual information in the visual haptic parallelity task improved parallel setting considerably, supposedly by increasing the influence of the allocentric reference frame. We found an additional beneficial effect when participants had to draw the orientation of the bar, probably because the drawing movement was guided by the arm/shoulder, thus reducing the influence of the hand-centered egocentric reference frame. With regard to gender differences our findings are consistent with the view that women profit to the same extent from the use of an allocentric reference frame in parallel setting tasks, but are most likely less efficient in overcoming the egocentric bias of the hands.

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