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How robust are the deviations in haptic parallelity?

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Abstract

Several studies have shown that physically parallel bars do not feel parallel and vice versa. The most plausible cause of this deviation is the biasing influence of an egocentric reference frame. The aim of the present study was to assess the strength of this egocentric contribution. The deviations from veridicality were measured in six experiments where subjects were presented with either haptic or visual information about parallelity or their deviations. It was found that even direct error feedback (either haptically or visually) did not even nearly result in veridical performance. The improvements found were attributed to a shift in focus towards a more allocentric reference frame, possibly reflecting the same mechanisms as found in delay and noninformative vision studies. We conclude that the illusionary percept of haptic parallelity is rather robust and is indeed caused by a strong reliance on an egocentric reference frame.

PsycINFO classification: 2320

Keywords: Haptic spatial perception; Egocentric; Allocentric; Frame of reference; Training; Feedback; Parallel

1. Introduction

Several studies have shown that what is perceived haptically as parallel deviates far from physically parallel (e.g., Kaas & Van Mier, 2006; Kappers, 1999, 2003; Kappers & Koenderink, 1999; Newport, Rabb, & Jackson, 2002; Zuidhoek, Kappers, Van der Lubbe, & Postma, 2003). Interestingly, these deviations are not random but very systematic: in order to feel parallel, the right bar has to be rotated clockwise with respect to the left bar. The necessary rotation is subject-dependent and can be as large as 90° depending on the distance between the bars (Kappers, 2003).

Subsequent studies have focussed on finding the explanation for these large systematic deviations (for an overview, see Kappers, 2007). A key observation was that the pattern of deviations pointed towards the biasing influence of an egocentric reference frame. In this respect, it is important to note that "parallel" in an egocentric reference frame is not necessarily the same as "parallel" in an allocentric reference frame. In a hand-centered reference frame, for example, "parallel" would mean "the same orientation with respect to the hand, irrespective of the location and orientation of the hand". In a body-centered reference frame, "parallel" could mean "the same orientation with respect to concentric circles around the body midline". For all subjects in all parallelity experiments, the parallelity settings were found to lie in between "parallel" in an allocentric reference frame (that is, veridically parallel) and "parallel" in an egocentric reference frame, although the exact nature of the egocentric reference frame is still somewhat open (e.g., Kappers, 2003, 2004, 2007; Kappers & Viergever, 2006). The hypothesis is that haptically parallel is a weighted average of allocentrically parallel and egocentrically parallel.

The most likely candidates for the egocentric reference frame are hand-centered and body-centered reference frames, or even more likely, a combination of the two (Kappers, 2007). Various findings support this hypothesis. Most papers dealing with haptic parallelity show that the deviations strongly correlate with hand orientation. Most

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directly this is shown in an experiment with an extended field of bars (Kappers, 2005). Subjects were asked to make 15 bars at various locations all parallel to each other; after the experiment, their spontaneous hand orientations at the same locations were measured. The results show a strong correlation between haptic settings and hand orientations. In addition, Kappers (2007) shows that a weighted average model fits the data quite well. She also shows that a weighted average model with a body-centered egocentric reference frame likewise fits the data quite well, albeit that for most subjects the probability of a hand-centered model is larger.

Kappers and Viergever (2006) explicitly instructed subjects to orient their hands in a specific way (i.e., straight forward, divergent or convergent) while performing the parallelity task. Thus, in their experiment subjects were well aware of the orientation of their hands with respect to an outside frame of reference and thus of the misalignment of the ego- and allocentric reference frames. Even so, performance was far from veridical in the parallelity task; when their hands diverged (i.e., were rotated outwards), the deviations increased and when their hands converged (i.e., were rotated inwards), the deviations decreased. In fact, subjects more or less ignored the orientation of their hands. The weighted average model could predict how the deviations would change (either increase or decrease) with the imposed hand orientations of their subjects. Interestingly, it is not the case that subjects are not able to compensate for hand orientation, since in experimental conditions where they have to estimate or adjust clock times (Hermens, Kappers, & Gielen, 2006; Zuidhoek, Kappers, & Postma, 2005), their deviations are much smaller.

Additional evidence for the biasing influence of an egocentric reference frame is given by the reversal of the oblique-effect (e.g., Kappers, 2003; Kappers & Viergever, 2006) and the much better performance in a mirroring task as opposed to tasks adjusting parallel or perpendicular bars (Kaas & Van Mier, 2006; Kappers, 2004).

The idea that measurements can be influenced by body (part) orientation is not new. Various other authors have reported very different experiments in which also substantial deviations are found (e.g., Carrozzo & Lacquaniti, 1994; Flanders & Soechting, 1995; Paillard, 1991; Soechting & Flanders, 1992). They argue likewise that the deviations in these experiments are due to a biasing influence of an egocentric reference frame. Depending on the experimental conditions, this egocentric reference frame can have various origins, such as the arm (e.g., Flanders & Soechting, 1995) or the hand (e.g., Carrozzo & Lacquaniti, 1994).

It is an interesting and important question whether and how this egocentric bias can be influenced. Zuidhoek et al. (2003) have shown that in the parallelity experiment, a time delay in between the exploration of the reference bar and the setting of the test bar results in significantly smaller deviations. A delay supposedly induces a shift from the egocentrically biased spatial representation towards a more allocentric one (e.g., Rossetti, Gaunet, & Thinus-Blanc, 1996). Newport et al. (2002) showed that also noninformative vision (i.e., vision that is not of any relevance for the task at hand) causes a significant reduction in the size of the deviations. Later, this result was reproduced and extended by Zuidhoek and colleagues (Zuidhoek, Visser, Bredero, & Postma, 2004). The idea is that vision plays an important role in spatial cognition (e.g., Thinus-Blanc & Gaunet, 1997) and therefore might provide sensory awareness for a more allocentric representation.

The focus of the present series of experiments is to assess the strength of the egocentric contribution to the spatial representation in circumstances where subjects are confronted with either haptic or visual information about parallelity. On the basis of the effects of delay and noninformative vision, one might expect that improvements (i.e., reductions of the deviations) are certainly possible. In this respect one should realize that although the improvements reported for delay and noninformative vision are significant, they are also quite small (just a few percent of the total deviation). On the other hand, introspective reports of ourselves and numerous subjects and visitors, indicate that knowing that bars are parallel and even seeing these parallel bars, does not achieve that they also feel parallel.

Therefore, our hypothesis is that the egocentric contribution to the perception of parallelity is very strong and hard to ignore, either consciously or unconsciously. However, in conditions where subjects are asked to focus on some kind of allocentric reference frame, small improvements are likely to occur. Our aim is not to teach our subjects how to perform veridically, but to measure whether their perception changes after various training or feedback procedures. If their deviations remain substantial after training, it has to be concluded that the misperception of parallelity is an illusion strongly relying on our egocentric reference system. If, on the other hand, subjects improve after specific training or feedback, we gain information on how various factors, such as vision and error feedback may influence haptic perception and the relative dependence on different reference frames.

In a baseline condition, subjects will be tested without any training or feedback. In Experiments 2–4, subjects will receive some form of training (either haptically, visually or both), but they are not told explicitly that they make large errors. In Experiments 5 and 6 they are shown, either visually or haptically, their deviations from veridical settings. In all experiments subjects will be tested before, during, and after the training.

2. General methods

2.1. Subjects

In all experiments, eight different subjects participated. Their handedness was assessed by means of a standard questionnaire (Coren, 1993). Most of them were students of Utrecht University. All subjects participated on a voluntary basis, they were paid for their efforts and they were naive with respect to the task and the research aims.

2.2. Set-up and stimuli

The set-up and stimuli were the same as in some of our previous studies (Kappers, 2003, 2004). This set-up consisted of a large, 74 cm high, table covered with a plastic layer on which 15 protractors with a radius of 10 cm were printed. The spacing between the protractors was 30 cm in the left–right direction and 20 cm in the forward direction. In the current experiments, only two of the protractors were used, namely, those placed at co-ordinates (60 cm, 20 cm) and (−60 cm, 20 cm). The subject was seated in front of co-ordinates (0, 0) on a stool that was adjustable in height. Shoulder height was fixed at about 1.1 m. Subjects were not allowed to touch the edges of the table. Aluminium bars with a length of 20 cm and a diameter of 1.1 cm were placed on the protractors; a small pin, which fitted in a hole in the centre of the protractor ensured that the bars could be rotated freely without being displaced. Due to a thin iron plate in between the plastic layer and the table, small magnets attached to the bottom side of the bars increased the resistance of the bars against movements, so that they remain in the orientation adjusted by either the experimenter or the subject unless rotated purposely. At one end the bars ended in an arrow-shape so that the orientation could be read off easily with an accuracy of about 0.5°.

Four reference orientations were tested, namely, 0°, 45°, 90° and 135°. The 0° orientation was aligned with the left–right axis of the table; increasing angular values signify a counterclockwise rotation. In the present study, orientation was only varied to provide variation in stimulus presentation (for a discussion of possible influence of reference orientation, see Kappers, 2004). The reference bar could appear at either location; given the location for the reference bar, the test bar was positioned at the other location. In all experiments, a block consisted of a single presentation of all the 8 different combinations of reference bar orientation and location. The order of presentation within a block was random.

2.3. Procedure

Before the actual experiments started, it was verified that the subjects understood the notion "parallel". They were shown the two bars, but not the set-up. The experimental procedure up to the first break was explained to them. They took their seat behind the table, blindfolded themselves, and only then the cloth concealing the set-up was removed. Next, they were presented with a test trial to make them comfortable with the experimental task. They were instructed to rotate the test bar in such a way that it felt parallel to the reference bar. They had to make sure that the arrow heads of the two bars pointed in the same direction. They were not given any feedback as to the accuracy of their setting.

The actual experiment consisted of three phases that were separated by a break of about 10–15 min:

Test: This first phase was to establish the average deviation of a subject. The subject was presented with five blocks of stimuli. Each trial had a maximum duration of 10 s.

Training: In Experiments 1–4, the second phase provided the subject with some information about correct settings. This information was given for 70 s and it was followed by one block of trials; each trial had again a maximum duration of 10 s. This sequence was repeated five times. In Experiments 5 and 6, the subject received some form of feedback on his/her setting. The total feedback time was again about 70 s per block. Again there were five blocks.

Post test: The third phase was identical to the test phase and was conducted to determine whether performance of the subject had changed or not.

Total time per subject was about 2 h.

2.4. Data analysis

Deviations are defined as "orientation of the left bar" minus "orientation of the right bar", irrespective of whether the reference bar is located at the right side or the left side. In this way, a positive deviation implies that the right bar is rotated clockwise with respect to the left bar.

We performed repeated measurements ANOVAs on both the overall and the individual results. If there was a significant main effect of phase, we did pairwise comparisons (*t*-tests) in which we corrected for multiple comparisons with a Bonferoni adjustment. In our statistical analyses we use a significance level of 5%. In the figures, significant differences will be indicated by an asterisk.

3. Experiment 1: no training

The motivation for this first experiment is straightforward: if we want to determine whether or not subject's performance improves after some kind of training, it is essential to know whether any changes in performance are indeed a consequence of the training. Therefore, performance is measured in a setting very similar to that of the training experiments, but with the critical difference that no training is provided. In this way, it will be investigated whether "spontaneous" changes (either improvements or deteriorations) over time occur.

Based on our previous studies we do not expect subjects to improve spontaneously. Some of our subjects in previous studies participated in a number of experiments over a long period of time, but there are no indications that their performance improved or changed.

3.1. Methods

All eight subjects were right-handed; four were males (AB, AL, BB and YL) and four were females (DB, IL, KE and MM). Their ages ranged from 19 to 25.

As Experiment 1 was aimed at testing whether performance improved over time by itself, the "training" here consisted of 70 s of doing nothing.

3.2. Results

In Fig. 1a, signed deviations averaged over all subjects and all blocks of trials within a phase are shown. Numbers 1, 2 and 3 refer to test phase, training phase and post test phase, respectively. Average deviations are 59°, 60° and 61° for the three phases. Not surprisingly, a repeated measurement analysis does not reveal any significant differences between the three phases. However, as can be seen in Fig. 1c, individual subjects may differ substantially. Their average deviations in the test range from 42° for subject KE to 77° for subject DB, while the deviations in the post test range from 31° for subject YL to 79° for subject IL. The influence of "training", in this case the influence of time past, is clearly subject-dependent. Four subjects do not show any effect of time (AB, DB, IL and KE), three subjects perform increasingly worse (AL, BB and MM), and only one subject improves over time (YL). For YL the improvement occurs after the third block of the test phase, where performance suddenly jumps to that of the later phases. Possibly, this subject changed strategy after just a few trials.

Fig. 1b shows the average deviations per block of 8 trials and it can be seen that these are rather constant over time.

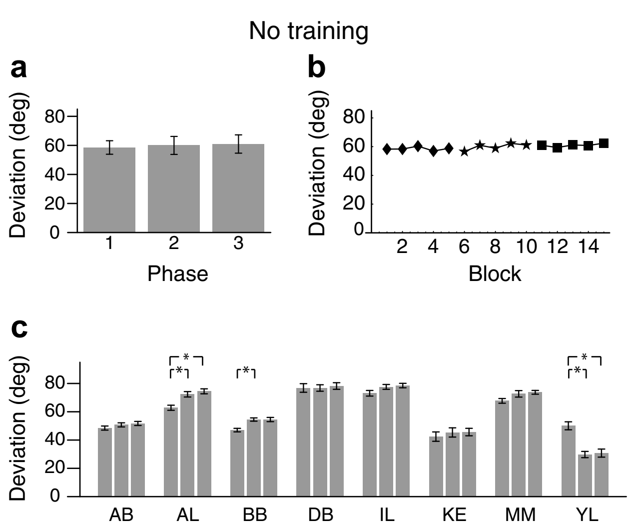

Fig. 1. Experiment 1: no feedback. (a) Signed deviations averaged over all subjects and all blocks of trials within a phase are shown. Test phase, training phase and post test phase are numbered 1, 2 and 3, respectively. (b) Average results per block. (c) Signed deviations averaged over all blocks of trials within a phase for all subjects participating in this experiment. The error bars indicate standard errors of the mean. An asterisk indicates that there is a significant main effect of phase. If there are also significant contrasts, these are further specified with the brackets.

It is also of interest to look at the spread of the data. For each condition (combination of reference orientation and reference location) a standard deviation is computed over the five repeats of a subject in a certain phase. For the overall analysis, an average standard deviation is determined for each subject in each phase. The average standard deviations (averaged over subjects) are 10.5°, 9.0° and 8.5°, for test, training and post test phases, respectively. A repeated measurement analysis does not show an effect of phase on standard deviation.

3.3. Conclusions

As known from earlier research, the deviations are large, systematic and subject-dependent. More importantly, it is clear that subjects do not "spontaneously" improve when they perform the parallelity task repeatedly. This provides an important baseline for the subsequent experiments.

4. Experiment 2: haptic training

As might have been expected on the basis of previous research, the deviations found in Experiment 1 were quite substantial. Therefore, an interesting question was whether this illusion of parallelity would persist even after the subjects were haptically confronted with physically parallel bars. The training in Experiment 2 consisted of presenting subjects with a series of parallel bars, which they could touch in order to experience how parallel bars actually feel.

4.1. Methods

Eight right-handed subjects participated, five males (DW, JB, JC, MB and RZ) and three females (LE, YE and ZE). Their ages ranged from 19 to 23.

The training consisted of presenting the subjects with physically parallel bars that they were allowed to explore haptically. These parallel bars were presented at the same locations as the test and reference bars, and they had one of the following four orientations: 0°, 45°, 90° or 135°. All orientations were presented once during 15 s and in random order with a few seconds in between, so that total training time amounted to about 70 s. Subjects were told that they would feel a number of examples of actually parallel bars, without explicitly mentioning that the orientations were identical to those occurring in the tests. Such a series of four examples was followed by a block of eight trials, exactly like in the test and post tests. The complete training phase consisted of a sequence of five such combinations of 70 s training followed by a test block.

4.2. Results

In this second experiment, test, training and post test resulted in deviations of 49°, 40° and 38°, respectively, as can be seen in Fig. 2a. Although the average signed deviations in the training and post test are smaller than those in

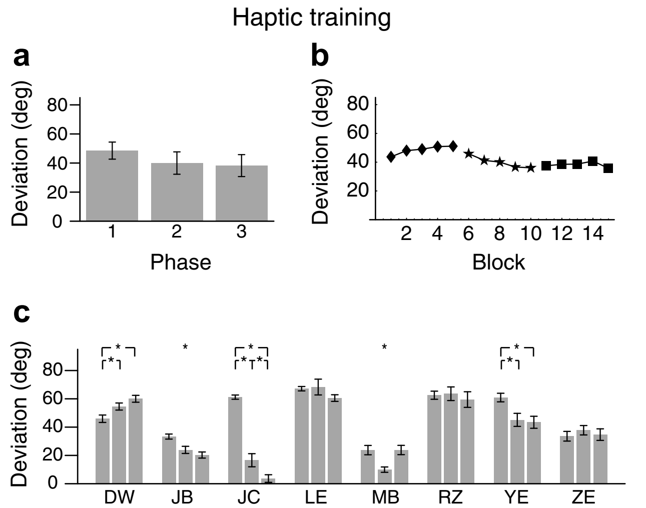

Fig. 2. Experiment 2: haptic training. For further explanation: see Fig. 1.

the test, these differences are not significant ($F_{2,14} = 1.8, p > 0.2$). Individual performance is shown in Fig. 2c. Deviations in the test phase range from 24° for MB to 67° for LE. The range of deviations in the post test is even bigger, namely, from 4° for JC to 61° for LE. For three subjects (LE, RZ and ZE) the three phases are not significantly different; the other five subjects do show a significant effect ($p < 0.05$).

Fig. 2b shows that the slight (but non-significant) improvement that could be detected in Fig. 2a, occurs gradually over the blocks during the training phase.

The average standard deviations are 10.1°, 17.4° and 12.7° for test, training and post test phases, respectively. An overall analysis does not show a significant effect.

4.3. Discussion and conclusions

Although the deviations are somewhat smaller after training, this effect is not significant. This can be understood when one considers individual performance, which varies from improvement, via no effect to deterioration.

5. Experiment 3: visual training

It has been shown that a time delay between exploring the reference bar and orienting the test bar, results in significantly smaller deviations (Zuidhoek et al., 2003). Zuidhoek and colleagues suggested that the role of visual imagery might play a role in strengthening the allocentric representation of space, which in turn would result in smaller deviations. Noninformative vision also causes a significant reduction of the size of the deviations (Newport et al., 2002; Zuidhoek et al., 2004). Stimulation of the importance of the allocentric contribution to the haptic representation of space might also be an explanation for this effect. In this third experiment, subjects were visually presented with correctly oriented parallel bars. Although vision was not available during the haptic settings, the training provided them with a clear view of the set-up that would possibly guide them in building up a visual representation of the task in question.

5.1. Methods

Four male (BL, JJ, TO and TZ) and four female subjects (BH, IG, MB and SH) participated in this experiment. They were right-handed, except for IG. Their ages ranged from 18 to 28.

The training was similar to that in Experiment 2, except that instead of feeling parallel bars, the subjects were allowed to see but not to touch the parallel bars. Subjects were asked to remove the blindfold during the training, watch the stimuli and sit with folded hands. After the series of four pairs of parallel bars, which lasted about 70 s, they had to blindfold themselves again. Subsequently, they were presented with a block of trials. Again, the complete training phase consisted of a sequence of five such combinations of 70 s training followed by a test block.

Some subjects commented that they found the training not very useful, because they were perfectly aware what "parallel" was and what they were supposed to do. Clearly, they did not realize that what they did, was not what they thought they did. They were nevertheless instructed to look at the bars.

5.2. Results

Test, training and post test resulted in average signed deviations of 51°, 46° and 47°, respectively (see Fig. 3a). Clearly, these three phases are not significantly different. Individual subjects show again idiosyncratic behaviour (see Fig. 3c). Four subjects (IG, MB, SH and TO) do not show any effect at all. TZ shows a significant increase in deviation after training. BL and JJ also show a significant effect of phase. In the case of JJ the trend is towards improvement, but BL's performance drops after the train-

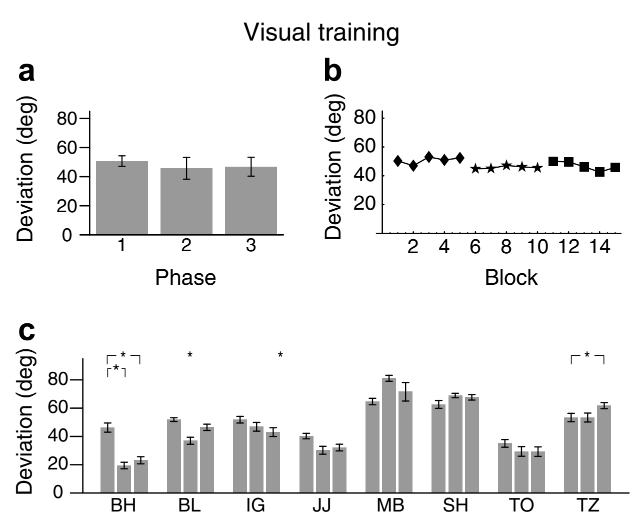

Fig. 3. Experiment 3: visual training. For further explanation: see Fig. 1.

ing stops. The only subject that clearly improves after training is BH.

Fig. 3a showed that there is hardly any change in performance during this experiment. Fig. 3b confirms that this also holds true for individual blocks of trials.

Standard deviations do not depend significantly on phase (10.9°, 11.4° and 11.5° for test, training and post test, respectively).

5.3. Discussion and conclusions

It was hypothesized that viewing the set-up and parallel bars possibly would strengthen subjects' visual representation and consequently lead to somewhat improved performance. However, this training consisting of viewing parallel bars did not result in improved performance. Although individual subjects might improve, other subjects clearly did not (or even performed worse). In this experimental condition, the information we gave our subjects was informative as opposed to noninformative, but it is hard to believe that such a difference would explain a lack of effect. Possibly, (non)informative vision works best during performance of the task and has little or no effect when presented at some other time. This is an interesting research question, which lies beyond the scope of the present paper.

6. Experiment 4: haptic and visual training

This fourth experiment was designed to investigate whether the combined training of Experiments 2 and 3 would lead to any improvements. In this case, the training consisted of presenting the subjects with parallel bars that they were allowed to touch and see. There are several arguments why improvement might occur. In Experiment 2 subjects were surprised and/or confused by what they felt during the training. Possibly, they did not even believe that the bars presented to them were indeed parallel. As "seeing is often believing", the combined visual and haptic exploration of parallel bars might convince them of the "correctness" of the stimuli. In Experiment 3, not all subjects were convinced of the use of the training. Most probably they will become aware of the discrepancy between what they can see is parallel and how that feels if they are allowed to explore parallel bars both visually and haptically. In the present experiment, seeing their hands and at the same time feeling parallel bars might implicitly stimulate subjects to use a more allocentric frame of reference (because they become aware of the misalignment between allo- and egocentric reference frames) and as a consequence, the deviations would be smaller.

6.1. Methods

Eight right-handed, female subjects participated in this experiment. Their ages ranged from 19 to 58, with an average of 27 years.

The training consisted of a combination of the information given to the subjects in Experiments 2 and 3. They were not only allowed to feel the examples of parallel bars, but they were also allowed to simultaneously see them. Otherwise, the procedure was identical to that of Experiment 3.

6.2. Results

In Fig. 4a, the results of this fourth experiment can be seen. Test, training and post test resulted in average signed deviations of 59°, 49° and 50°. A repeated measurement analysis shows a significant effect of phase ($F_{2,14} = 6.8$, $p = 0.008$). Pairwise comparisons revealed that this effect is due to a difference between test and training ($p = 0.031$). Surprisingly, only two of the eight subjects show a significant effect of phase, namely, HH and WH (see Fig. 4c). For both subjects, the test phase differs significantly from the training and post test phases.

The analysis of overall effects revealed a significant improvement between the test and the training phases. In Fig. 4b it can be seen that, possibly, this might be attributed to two small effects. First, a growing deviation during the test phase and second, a gradual improvement during the training phase.

Average standard deviations were 10.9°, 15.1° and 14.1° for test, training and post test, respectively. An overall analysis did not show a significant effect.

6.3. Discussion and conclusions

Providing both haptic and visual information relevant to the task, resulted in a small but significant improvement. However, it should be noted that this effect was only significant for two out of eight subjects. In this experimental condition, subjects might have been surprised or confused how parallel bars actually feel, but since they were also allowed to see the bars, they should have been convinced

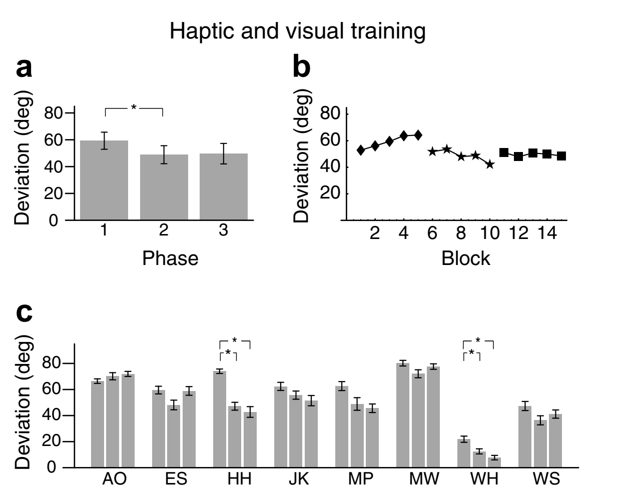

Fig. 4. Experiment 4: haptic and visual training. For further explanation: see Fig. 1.

that the bars were indeed physically parallel. This combination probably strengthened their allocentric representation of the configuration, resulting in a reduction of the deviations.

7. Experiment 5: haptic feedback

During the training in Experiment 2 subjects were haptically presented with bars that were physically parallel and often this led to surprise and confusion. They realized that what they felt as being parallel was not the same as what was actually parallel, but they found it hard to infer the connection between the two sets. In Experiment 4 they were haptically and visually shown parallel bars, but of course, this did not give them direct information on how their haptic percept of parallelity deviated from physically parallel. The purpose of this fifth experiment is to investigate whether performance of the subjects improves when they receive direct haptic feedback about their deviations.

7.1. Methods

Eight right-handed subjects participated in this experiment; six were females (DA, DB, LW, MV, NW and VL) and two were males (GO and MK). Their ages ranged from 19 to 22.

During the training phase, subjects received immediate feedback about their setting. At the end of a trial, they were asked to lift their hands and put them immediately back in place after the experimenter rotated the test bar to the correct orientation. They were allowed to feel this correct setting during 7.5 s. As there are eight different combinations of reference orientation and location, the total training duration was again about 70 s per block (including a few seconds in between trials). The total training phase consisted of five such sequences.

7.2. Results

Test, feedback, and post test phases resulted in averaged signed deviations of 55°, 39° and 33°, respectively (see Fig. 5a). Although the effect of phase is significant ($F_{2,14} = 7.5, p = 0.006$), none of the pairwise comparisons is significant. Six of the individual subjects show a significant effect of phase: DA, GO, LW, MK, MV, and NW. NW progressively performs worse, whereas the other five subjects show improvements (see Fig. 5c).

Fig. 5b shows the average deviations over blocks of trials. Interestingly, this figure shows a gradual improvement during the feedback phase.

Averaged standard deviations were 12.9°, 32.6° and 20.9° for test, feedback and post test phases, respectively. The effect of phase was significant ($p = 0.002$). Pairwise comparisons showed that both the difference between test and feedback phases ($p = 0.022$) and the difference between feedback and post test phases were significant ($p = 0.003$).

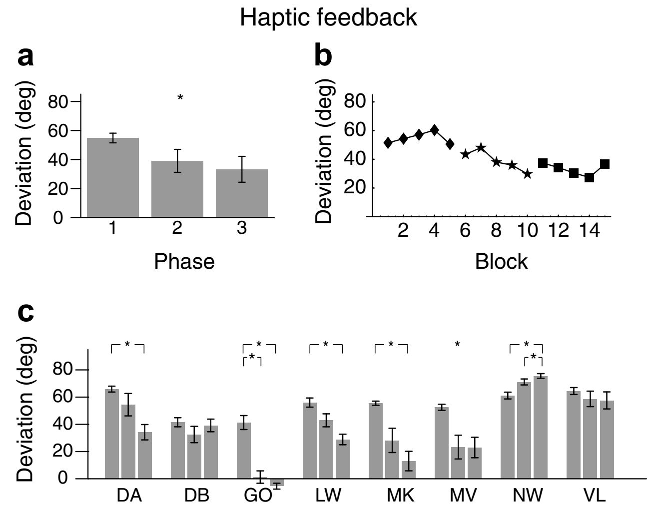

Fig. 5. Experiment 5: haptic feedback. For further explanation: see Fig. 1.

7.3. Discussion and conclusions

Haptic feedback during the training clearly results in a substantial reduction of the deviation, although from the results of individual subjects, it can be seen that the effect of training is quite idiosyncratic. Interestingly, the uncertainty (as expressed by standard deviations) increases after training: subjects perform better but their deviations vary more from trial to trial. Although “increased uncertainty” might have caused this increase, an alternative explanation, especially during the feedback phase, might be that subjects are trying out different strategies to improve their performance.

In Fig. 5b it could be seen that performance gradually improves during the feedback phase, whereas improvement stops abruptly when the post test starts. From this figure, it is clear that the decrease in deviations is not yet saturated. Therefore, it seems quite likely that further improvement might be possible if more feedback blocks would have been presented.

8. Experiment 6: visual feedback

Some subjects in Experiment 3 experienced the visual training as not very useful since they did not realize that their haptic settings deviated substantially from veridical. As a consequence, the influence of visual imagery might have been limited. In this final experiment, subjects are visually confronted with their haptic settings. Possibly, this confrontation with their deviations guides them in building up a visual representation relevant to the task.

8.1. Methods

Eight subjects participated in this experiment, six females (AK, CC, LB, MA, MV and PD) and two males (JB and JO). Two of them were left-handed (CC and JO) and the others were right-handed. Their ages ranged from 18 to 22.

During the training phase visual feedback was provided. After a trial, subjects were allowed to remove the blindfold and look at their setting for 7.5 s. After that, they had to put on the blindfold again and they were presented with the next trial. The total training duration was again about 70 s per block (including a few seconds in between trials). The total training phase consisted of five such sequences.

8.2. Results

Test, feedback, and post test phases resulted in averaged signed deviations of 67°, 51° and 44°, respectively (see Fig. 6a). Although the effect of phase is significant (Greenhouse-Geisser: $F_{1.16,8.09} = 6.7, p = 0.029$), none of the pairwise comparisons is significant. However, some of the individual subjects do show a significant effect of phase: AK, CC, JB, JO, and MV (see Fig. 6c).

In Fig. 6b the overall average deviations are shown for the individual blocks of eight trials. It can clearly be seen, that the significant improvement that was found, occurs gradually during the feedback phase.

Test, feedback and post test phases resulted in average standard deviations of 11.9°, 19.8° and 14.1°, respectively. The overall effect of phase on standard deviation was significant ($p = 0.047$).

8.3. Discussion and conclusions

Direct visual feedback caused a substantial improvement of performance, but again the effect is subject-dependent. Not all subjects profit from the information offered to them. Like in the haptic feedback experiment (Experiment 5) the standard deviations increase, revealing the increased uncertainty of the subjects. Alternatively, the larger standard deviations might indicate that subjects are trying out different strategies, with some strategies giving better (i.e., more veridical) results than others.

In Fig. 6b it could be seen that, like in the haptic feedback experiment, performance improves gradually during the feedback phase. Performance stabilizes as soon as the post test starts. Although the decrease in deviations during the feedback phase seems to level off somewhat toward the end, it might be the case that there is room for more improvement if the feedback phase would continue longer.

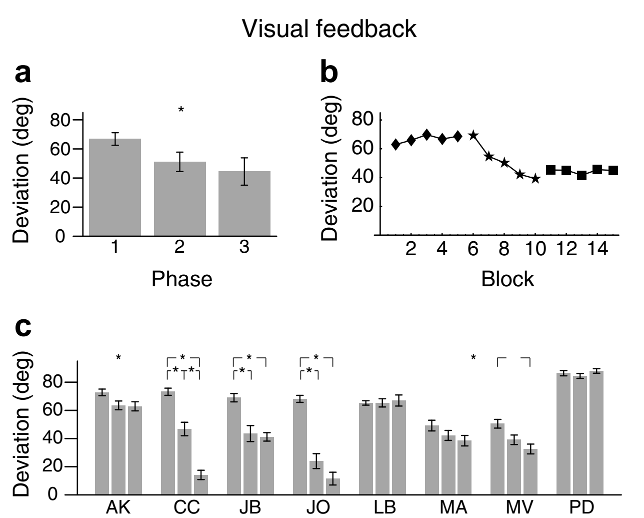

Fig. 6. Experiment 6: visual feedback. For further explanation: see Fig. 1.

9. General discussion and conclusions

The conclusion that can be drawn from these six experiments is that the deviations in the haptic perception of parallelity are indeed quite robust. It is certainly not the case, as many researchers expected, that showing subjects their deviation immediately reduces their subsequent deviations to almost zero. We can therefore describe this effect as an illusion of haptic parallelity. Even obvious training methods (Experiments 2–3) are not capable of really changing the percept. Only a combination of haptic and visual training (Experiment 4) resulted in a small but significant improvement. Error feedback (Experiments 5–6) resulted in somewhat larger improvements, although even in these cases the remaining deviations are large (33° and 44°, respectively). However, during the feedback phase the deviations gradually decreased, so one might expect smaller and possibly even random deviations around zero if the feedback phase would be extended.

In all six experiments there are clear interindividual differences, not only in the size of the deviations but also in the effect of training and feedback. This wide distribution of deviation size was already known from earlier research (Kappers, 2003), where the deviations in the same experimental condition as in the test phase here, were found to range from 8° for the best subject to over 90° for the subject with lowest performance. The effect of training is strongly idiosyncratic without any clear relation to the performance before training. That is, subjects' performance might improve, remain unchanged or deteriorate, irrespective of their performance in the test phase.

It is of interest to have a closer look at the experimental conditions where improvements did or did not occur. Noninformative vision (Newport et al., 2002; Zuidhoek et al., 2004) caused a reduction of the deviations in similar parallelity experiments and these authors argued that vision, even when noninformative, strengthens the reliance on an allocentric frame of reference. Of course, it could be that noninformative vision is only effective when present during performance of the task. However, Zuidhoek et al. (2003) showed that a delay between reference and test also causes improvement, so temporal overlap might not be essential. Therefore, it was hypothesized that showing the subjects the set-up and a number of pairs of parallel bars might have a similar improving effect in our experiment. We indeed found a reduction of the deviations, but the improvement was far from significant. In this context, it should be noted that in the studies of Newport, Zuidhoek and colleagues, the improvements were also just a small percentage of the total deviation and the effects were far from canceling the bias of the egocentric reference frame. Zuidhoek et al. (2004) report an improvement of 5 degrees, which is similar to the effect we found. Newport et al. (2002) report an even smaller effect, but since in their experiment the distances and as a consequence also the deviations are much smaller, these numbers should not be compared directly.

Haptic information (Experiment 2) or visual information (Experiment 3) alone hardly had an effect, but the combination of haptic and visual information (Experiment 4) proved useful. Subjects may be surprised by the haptic information, but vision will convince them that the bars they feel are indeed parallel. As a consequence, the visual information becomes relevant instead of useless, as they might have experienced in the vision only experiment. When they realize that they cannot fully "trust" their haptic system, they possibly consciously or unconsciously try to shift their focus towards a more allocentric reference frame resulting in a smaller egocentric bias. The resulting effect, a slight shift towards a more allocentric representation, is similar to that found in the delay and noninformative vision studies, where subjects are not aware of their deviations. Possibly, the underlying mechanisms for this shift are the same.

In a series of experiments, Millar and Al-Attar (2002) have investigated how they could teach subjects to become insensitive to the well-known Müller-Lyer illusion that is also prevalent in touch. Interestingly, they obtained the best results (that is, almost no effect of the illusion) when they instructed their subjects to focus on a body-centered (and thus an egocentric) frame of reference in combination with the advice to ignore the fins. Instructing their subjects to pay attention to allocentric cues from scanning did not reduce the illusion. It is questionable whether a more explicit instruction to focus on an egocentric reference frame might have reduced the deviations in our experiments, as the deviations are considered to be caused by an egocentric bias. Moreover, our task is essentially an allocentric task unlike the comparison of lengths in the Müller-Lyer illusion; it is unclear, how focusing on an egocentric reference frame would help the subjects. So, instead of attributing the improvements found in our various experiments to an increased focus on an egocentric reference frame (like in the case of the Müller-Lyer illusion), we take the opposite view and propose that the balance between the weights of the allo- and egocentric reference frames is somewhat shifted towards the allocentric one. This is in line with the results found and explanations given in the noninformative and delay studies (Newport et al., 2002; Zuidhoek et al., 2003; Zuidhoek et al., 2004).

In all experiments (except of course Experiment 1), the standard deviations in the training phase were larger than those in the test phase. On the one hand this might indicate the increased uncertainty or confusion of the subjects. Even though subjects made large errors in the test phase, they were apparently not aware of these errors and as a consequence they were reasonably confident about their settings. When confronted with parallel bars or with their deviations they became confused and much less confident, resulting in a larger spread of their settings. On the other hand, when confronted with the information that their haptic settings are apparently not correct (in the training and feedback phases of the experiments), subjects might consider alternative strategies to perform the task. If they experiment with different strategies from trial to trial, some of them would lead to more veridical results than others, and as a consequence standard deviations would increase. Most likely, the higher standard deviations are caused by a combination of these reasons.

As stated in the Introduction, it was not our goal for this paper to teach our subjects to perform veridically, but to measure whether or not their performance can be influenced by various training and feedback methods. Nevertheless, it is of interest that especially the feedback experiments show gradual improvements during the feedback phase. This suggests that performance might further improve after a prolonged feedback phase. One may wonder what exactly changes during this phase. Introspective reports of some of our subjects mention "learning of tricks" without a "change in percept", but other subjects noticed that physically parallel bars started to feel parallel as well. As we did not systematically record such reports, it is impossible to use them as basis for any conclusions.

von Helmholtz (1909/1962) described the adaptation to prismatic displacement: a person looking through prismatic goggles that displace the visual field laterally, adapts to this new situation quickly if proper feedback is given. In the literature there is agreement that this process involves some kind of spatial remapping (e.g., Redding & Wallace, 2006). There are more examples where adaptation is explained by or described as spatial remapping (e.g., Mosier, Scheidt, Acosta, & Massa-Ivaldi, 2005; Wang & Sainburg, 2005). In a number of our experiments, subjects also seem to slowly adapt to a new situation and that may likewise involve spatial remapping. The nature of spatial remapping is not well understood and at least in the case of prism adaptation, there is discussion whether spatial remapping is a form of motor learning or perceptual learning (Redding & Wallace, 2006). We argue that the tasks in our experiments are mainly perceptual tasks, so if spatial remapping indeed occurs, it will probably be a form of perceptual learning.

A remaining question is whether the significant and rather persistent egocentric biases have any functionality. In this respect, one should consider that haptic information is typically interpreted and used in situations of direct percepto-motor actions (such as shaping one's hand when stumbling upon an unseen object). For orientation processing it then is vital to place the hand in an appropriate orientation for the motor activity to be performed. One thus could argue that there is preponderance of processing the haptic input within a hand-oriented egocentric reference frame. Since this serves everyday object handling, this would also have a clear ecological significance.

Notwithstanding all the improvements that occur or may occur during longer training or feedback sessions, we conclude that the illusionary percept of haptic parallelity is rather robust and is caused by a strong reliance on an egocentric frame of reference.

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