# Haptic Space Processing –
# Allocentric and Egocentric Reference Frames

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**Abstract**  In this paper a haptic matching task is used to analyze haptic spatial processing. In various conditions, blindfolded participants were asked to make a test bar parallel to a reference bar. This always resulted in large but systematic deviations. It will be shown that the results can be described with a model in which an egocentric reference frame biases the participants' settings: What a participant haptically perceives as parallel is a weighted average of parallel in allocentric space and parallel in egocentric space. The basis of the egocentric reference frame is uncertain. There is strong evidence that at least a hand-centred reference frame is involved, but possibly a body-centred reference frame also plays a role.

**Résumé**  Dans cet article, une tâche de correspondance haptique est utilisée pour analyser le traitement haptique de l'espace. On a demandé à des participants auxquels on avait bandé les yeux, de faire un test de barre parallèle à une barre de référence. Cela a toujours donné des déviations importantes mais systématiques. Nous allons montrer que les résultats peuvent être décrits au moyen d'un modèle où un cadre de référence égocentrique fausse les réglages du participant. Ce qu'un sujet perçoit de façon haptique comme étant parallèle est une moyenne pondérée du parallélisme dans l'espace allocentrique et du parallélisme dans l'espace égocentrique. Le fondement du cadre de référence égocentrique est incertain. Il existe de fortes indications à l'effet qu'au moins un cadre de référence centré sur les mains est en jeu, mais qu'un cadre de référence axé sur le corps joue possiblement un rôle aussi.

One of the first to report on haptic processing of space was Blumenfeld (1937). In one of his experiments, he asked participants to produce haptically parallel lines on both sides of the midsagittal plane. He found a systematic pattern of converging and diverging lines: As long as the distance between the lines at the far end was less than the distance between the shoulder joints, the lines diverged; for larger distances, the lines were either parallel or sometimes even converged. He discusses his results in terms of tactual directions with respect to the "ego," and concludes that this egocentre is not necessarily the same in vision and in touch; shoulder, elbow and wrist may be involved in the case of haptic perception.

Quite a number of vision scientists were inspired by Blumenfeld's work, resulting in both experimental and theoretical papers on the properties of visual space. There was hardly any haptic follow-up, but in 1976 Brambring became interested in the metric of haptic space. He asked both blind and blindfolded sighted participants to make distance estimates in various experimental conditions. He observed a distortion of the shortest distance from the Euclidean metric to the city-block-metric. Using a different experimental paradigm, Lederman, Klatzky, and Barber (1985) also found that haptic distance estimates are far from veridical. Their study showed that for both blind and bindfolded sighted participants, the estimated distance between the endpoints of a path becomes increasingly larger as a function of the explored pathway. Since then, other studies confirmed that judgments of haptic spatial relations are most often not veridical (e.g., Faineteau, Gentaz, & Viviani 2003; Henriques & Soechting, 2003; Kappers & Koenderink, 1999).

The "ego" of Blumenfeld is now more commonly refered to as "egocentric reference frame." Klatzky (1998) gives as definition for an egocentric reference frame that in such a frame, locations are represented with respect to the particular perspective of the perceiver. As perceptual tasks may vary, so may the egocentric reference frames. Paillard (1991), Soechting and Flanders (1993), and Cohen and Andersen (2002) give a number of examples of such egocentric reference frames: visual-ocular motor space, within which targets are located in a retinocentric reference frame; visuo-locomotor space, in which eye and head spaces are integrated; body space; hand space; etc. The use of egocentric spaces may be clear; often it is important to relate the location of an object with respect to one's body, for example, when grasping the object.

A task may be considered allocentric whenever the instructions refer to spatial locations or relations without reference to the body. Conversely, if instructions refer to locating points or spatial relations relative to the body, the task is considered to be egocentric.
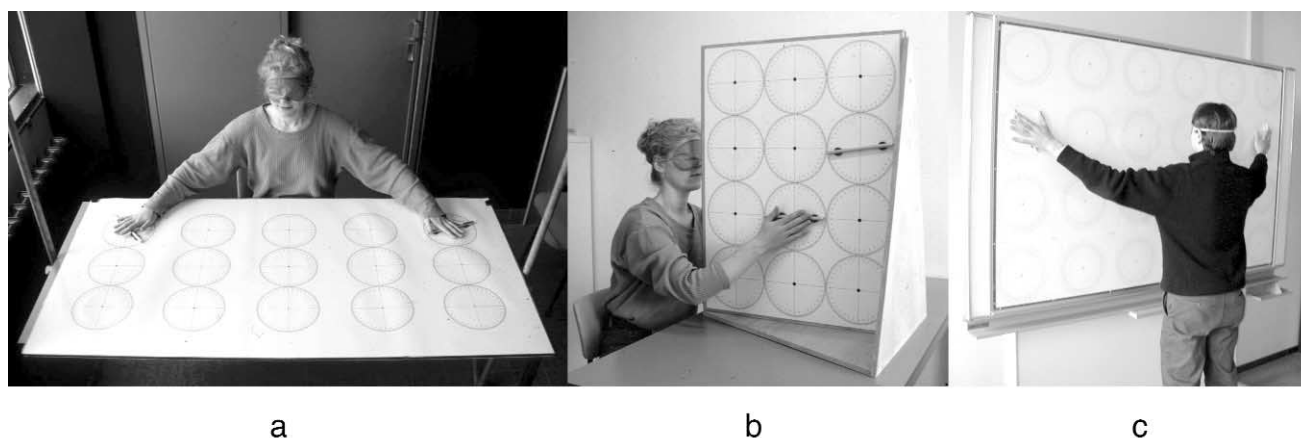
a                                                    b                                                    c

*Figure 1.* a) Horizontal set-up, b) midsagittal set-up, and c) frontoparallel set-up.

Sometimes, egocentric and allocentric versions of the same task may actually lead to the same results (for example, in mirroring – see later section), but most often the results will be different. Blumenfeld's participants were supposed to make the lines parallel in external space, which is therefore an allocentric task. However, apparently they were not able to do so as their settings showed a tendency towards egocentric space. Still, this tendency is not so strong that Blumenfeld's results can be explained fully by a description in terms of an egocentric reference frame. That is, also in egocentric space (either wrist, shoulder or elbow space) the lines that participants produced are not parallel.

Paillard (1991) gives a number of similar examples in which tasks are performed in a reference frame that is intermediate to an allocentric (external) reference frame and an egocentric one. Carrozzo and Lacquaniti (1994) likewise proposed a hybrid reference frame for visuo-manual coordination. Flanders and Soechting (1995) describe an extensive set of experiments in which they investigated whether the neural control of hand orientation is best described in a spatial reference frame fixed to space, as would be ideal for grasping and reaching movements. However, they find systematic errors that can be understood in terms of a reference frame intermediate to one fixed in space and one fixed to the arm. They also suggest that such an intermediate frame may be implemented both neurally and behaviourally.

The position that will be defended in this paper is that even though we are aware of a stable physical world outside ourselves, our perception of this world is strongly biased by our egocentric reference frame(s). In practice, it will turn out that it is often impossible to make allocentric judgments as we cannot ignore (not

even consciously) egocentric influences. As a consequence, the resulting judgments are neither allocentric nor egocentric, but lie somewhere in between. The exact weighting between the contributions of these two reference frames will depend on the experimental conditions and will also be dependent on the participant.

Such a weighted average of contributions of different reference frames provides a convenient way to understand and describe all the experimental results. Interesting in this respect is the study by Cohen and Andersen (2002), who describe the necessity of transforming sensory input into a reference frame suitable for motor output. They also investigated the neural basis of reference systems and they show evidence for a common reference frame for movement plans in the posterior parietal cortex. Possibly, the weighting of reference frames can likewise be found in this brain area, but that question lies beyond the scope of the present paper.

The subsequent experimental results might help our thinking about neuropsychological mechanisms that are involved in executing the various tasks. The existing evidence for weighted contributions of reference frames will be illustrated by means of a series of experiments that all make use of a "parallelity" paradigm. Among others, task instructions, locations, and planes were varied systematically.

### Parallelity Experiment

In the most general form of the parallelity experiment, blindfolded participants are asked to match the orientation of a test bar with that of a reference bar presented at another location. Typical set-ups used for these experiments are shown in Figure 1. Figure 1a shows the set-up and experimental configuration that are used most often: A blindfolded participant is seated
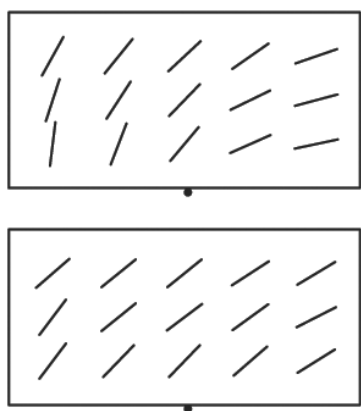
Figure 2. Top view of the parallel bars produced by two partici-pants using their right hand. Participants were seated against the table as indicated with the black dot.



Figure 3. Illustration of "parallel" in egocentric space. Frame of reference is the hand. The participant placed her hand in a natur-al way on all the positions; the bars have a fixed orientation with respect to her hand.

behind a table touching two bars that are far apart. One of the bars is oriented by the experimenter; the other bar has to be rotated by the participant in such a way that the two bars feel parallel. Usually no feedback is provided and the participant is given limited but suf-ficient time to perform the task.

In all variants of the task, large but systematic devia-tions from physically parallel are found. The systematic pattern can best be illustrated by the results from a uni-manual (either left or right hand) experiment in which the participant had to produce a whole field of parallel bars (Kappers, 2005). On the set-up of Figure 1a, 15 bars were placed, one on each circle, and the task for the participant was to make all bars haptically parallel to each other. Participants were allowed to go back and forth between all the bars as many times as they needed and typically took about 10 minutes to com-plete the task. Representative results from two partici-pants are given in Figure 2.

It can clearly be seen that although the result is far from physically parallel, the resulting pattern is certain-ly not random. For all participants and for both left- and right-hand performance of the task, a bar at the right side of the set-up has to be rotated clockwise in order to be perceived as parallel to a bar at the left side (Kappers, 1999, 2005). The amount of rotation needed depends on the distance between the two bars. It can also be seen in Figure 2 that this pattern is far more distinct in the upper graph than in the lower graph. An extensive study with 68 participants revealed that all participants show such deviations, but that the size of the deviations is indeed subject-dependent: Averaged over all participants the deviation between the two bars as shown in Figure 1a was 41°, but ranged from 8 to 91° (Kappers, 2003). This study further analyzed factors that might contribute to these deviations, like age,

handedness, arm length, arm span, shoulder width, shoulder height, and body height, but none of these factors was of decisive influence. The only factor that clearly was of influence is gender: Under the given conditions, the deviations produced by female partici-pants were on average 13° larger than those of males.

## Frames of Reference

As mentioned in the Introduction, the explanation for these deviations is sought in the biasing influence of an egocentric reference frame on performance in this allocentric task. In Euclidean geometry, a general definition of parallel lines is that these lines on a plane do not intersect if extended. In egocentric spaces, a slightly different definition is needed, since these spaces will be curved or otherwise deformed. Here a convenient definition of parallel is that parallel lines have the same orientation with respect to the reference frame. The advantage of this definition is that it also applies to allocentric space.

The exact nature of the egocentric reference frame for this particular task has yet to be determined. There are two likely candidates, either hand-centred or body-centred. In a hand-centred system, the orientation of the reference frame moves with the hand. This is illus-trated in Figure 3 where a participant placed her hand in a spontaneous way at several locations on a horizon-tal plane. Everywhere the bars have a fixed orientation with respect to the hand and therefore all bars are con-sidered to be parallel in hand-space. In a body-centred reference frame, the reference lines could be concentric circles around the body midline, with parallel lines being defined as having a fixed orientation with respect to these circles (see, for example, Kaas & Van Mier, 2006).

TABLE 1
Weighting Factors Expressed as Percentage of Egocentric Contribution

| Participant | Gender | Hand-centred | | Body-centred | Probability (%) |
| | | Right hand | Left hand | | Hand > Body |
| --- | --- | --- | --- | --- | --- |
| CH | f | 25 | 27 | 25 | 5 |
| CL | f | 22 | 20 | 25 | 19 |
| EV | m | 14 | 15 | 15 | 80 |
| HR | f | 31 | 19 | 27 | 100 |
| IL | f | 34 | 32 | 43 | 67 |
| LD | f | 37 | 34 | 44 | 82 |
| LG | m | 9 | 8 | 8 | 93 |
| ME | m | 19 | 19 | 21 | 100 |
| RK | m | 24 | 23 | 26 | 57 |
| RT | m | 31 | 32 | 34 | 76 |

*Note:* The allocentric contribution is 100 minus this percentage. In the hand-centred model, weighting factors are determined for right and left hands separately. Gender is indicated by f (female) and m (male). In the right column the probabilties are given that the hand-centred model gives a better description than the body-centred model.

Although in many experimental conditions concerning the parallel-set task, the influence of these two egocentric reference frames cannot be distinguished, one experimental manipulation (to be described later) clearly supports the contribution of a hand-centred reference frame. However, it should be noted that the main message will be that perceptually parallel is the result of a weighted average of allocentrically parallel and egocentrically parallel. The exact choice of egocentric reference frame is irrelevant; most likely more than one egocentric reference frame will play a role.

### Hand-Centred Model

Haptically perceived fields of parallel bars, like those shown in Figure 2, were measured three times for 10 blindfolded participants for both their right and their left hands (Kappers, 2005). The set-up used is that of Figure 1a. Participants were allowed as much time as they needed to perform the task to their own satisfaction. An example of haptically parallel bars produced by participant HR using her right hand can be seen in Figure 4a. An allocentric representation was obtained by fitting an array of objectively parallel lines that overlaps maximally (Figure 4b) with the participant's parallelity settings (Figure 4a). In Figure 4c, allocentric model (Figure 4b) and measurements (Figure 4a) are compared. The circular arcs and the numbers (differences in degrees) indicate the mismatch between model and measurements.

After the parallel-setting task was finished, egocentric hand-centred reference frames were determined by asking the same 10 participants (this time not blindfolded) to place their hand spontaneously (that is, in a natural way) at locations indicated by the experimenter.

The direction of their middle finger determined the orientation of the hand-centred reference frame at that specific location. This procedure was performed thrice for both right and left hands. In Figure 4d-left, the orientations of HR's right hand (averaged over the three sessions) are illustrated. In order to determine the weighting factors, the hand orientation settings (Figure 4d-left) were rotated for maximal overlap (Figure 4e-left) with the participant's settings (Figure 4a). Finally, the optimal weighting factors were determined per hand of each participant for the three haptic trials together. In this procedure, the total sum of squares of the difference between the model (a weighted average of Figures 4b and 4e-left) and the haptic settings over the three trials was minimized. The model fit is shown in Figure 4f-left. For both hands of each participant a weighting factor was determined (see Table 1). The numbers give the percentage of the contribution of the egocentric reference frame. These values are identical to the slopes of the correlation between haptic settings and hand orientation measurements as reported by Kappers (2005).

Although we can see in Figure 4f-left that the model fits the data quite well, we need a more objective measure to determine whether the model indeed gives a better description of the data than just assuming that the settings are veridical (as in the allocentric model of Figure 4c). Akaike's Information Criterion (AIC) or more precisely, the corrected AIC (AICc), is a suitable measure to determine the relative likelihood of two (or more) models (Motulsky & Christopoulos, 2003). The AICc is derived from information theory; instead of providing the significance of differences between models, it determines the probability that a model is better than
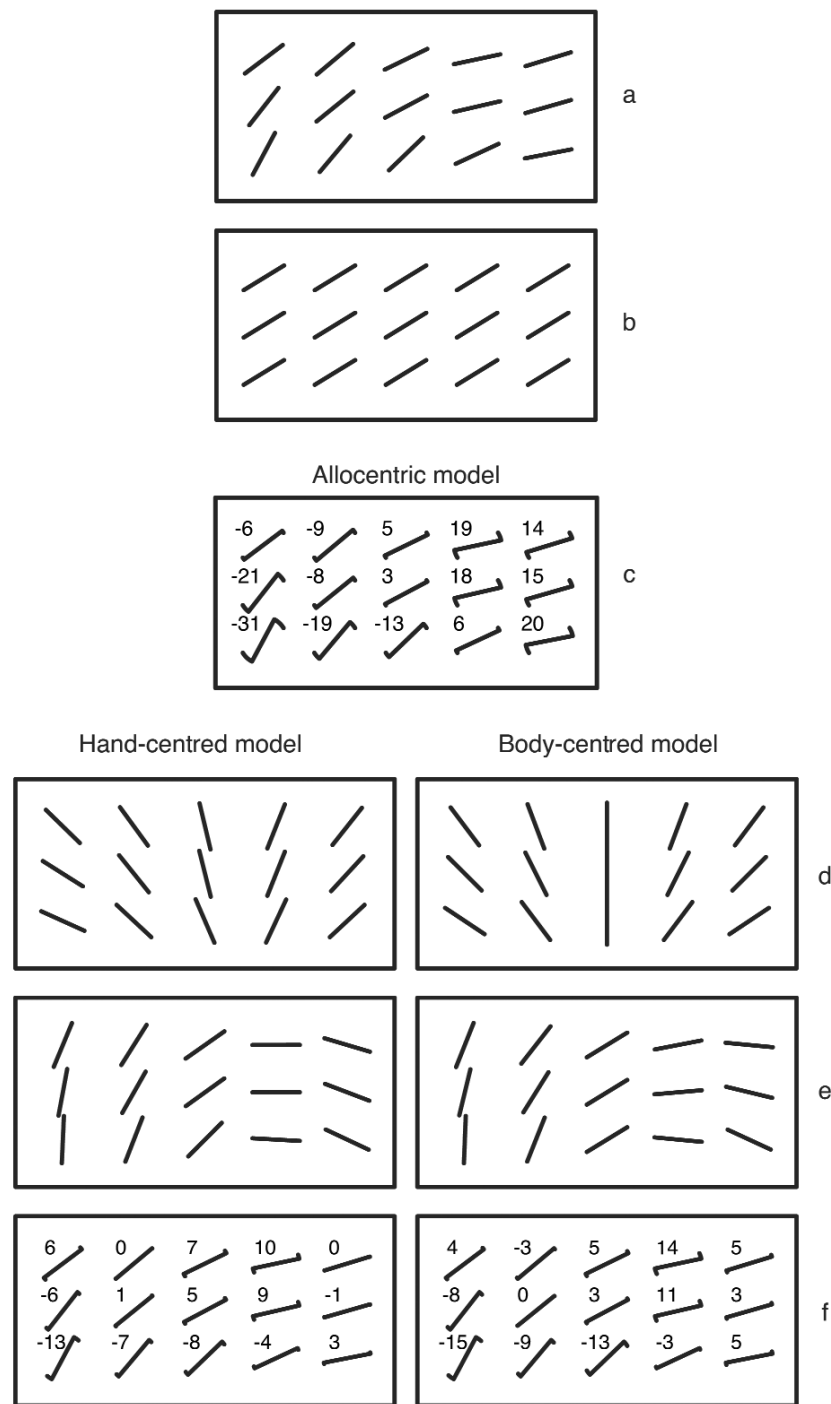
*Figure 4.* a) Settings of HR using her right hand; b) Objectively parallel lines that maximally overlap with the measurements; c) Comparison of allocentric model and measurements (difference between a and b). The circular arcs and the numbers (degrees) indicate the mismatch between model and measurements. d) Left: Orientation of HR's right hand at several locations measured along her middle finger. Right: Body-centred model with egocentre located at the body midline. e) Rotated version of d that maximally overlaps with a; f) Comparison of models and measurements. The models consist of a weighted average of the lines in b and e. The optimal weighting factors were 0.69 and 0.31 (hand-centred model) and 0.63 and 0.27 (body-centred model).

another model. The model with the lower AICc score is the more likely to be correct. AICc takes into account that the number of free parameters may be different for the different models. Using this AICc, it turns out that for all participants and for both their hands the weighted average model is better than veridical with a probability close to 1.0. This is even true for participant LG who has only a relatively small contribution of the egocentric reference frame.

It can be seen in Table 1 that the relative contributions of the two reference frames are strongly participant-dependent. Moreover, on average, females show larger egocentric weighting factors than males. Both these findings are consistent with previous research (e.g., Kappers, 2003). Interestingly, the weighting factors for the left and right hands are quite similar, the correlation coefficient being $R = 0.90$. Although the egocentric weighting factor could have been hand-dependent, support for a hand-centred reference frame is stronger if this factor is hand-independent. Subsequent experiments will demonstrate the validity of this model.

### Body-Centred Model

The same set of measurements (10 participants, both hands, 3 repeats, 15 bars) was also modeled by means of a body centred reference frame. For this model, the location of the body-midline has to be chosen. As all participants were seated right in front of the set-up, the approximate location of the body midline was (0, -20) cm (that is, 20 cm from the edge of the table). Figure 4d-right illustrates this frame of reference; in Figure 4e-right the lines are rotated to maximally overlap with the participant's settings. The optimal weighting factor was determined for the whole data set of a participant, again by minimizing the total sum of squares of differences between model (a weighted average of Figures 4b and 4e-right) and measurements. The weighting factors are given in Table 1. The tiny circular arcs and the numbers (differences in degrees) in Figure 4f-right indicate the very small mismatch between measurements and model fit. Using again the corrected Akaike Information Criterion (AICc), also this model has a probability close to 1.0 for all participants to be better than a veridical description of the data.

As both models give an adequate (and rather similar) description of the data, it becomes of interest to compare these two models directly. For most participants, the weighting factors of the two models are quite similar; only for two participants are the factors in the body-centred model clearly larger. However, this in itself does not say anything about the validity of the models. Fortunately, AICc makes a quantitative comparison possible because it takes into account the different

number of degrees of freedom in the two models (Motulsky & Christopoulos, 2003). The probabilities that the hand-centred model is better than the body-centred model are given in Table 1. For 8 out of 10 participants, the hand-centred model is clearly better; for the two remaining participants, the body-centred model wins.

### Parallel and Perpendicular Versus Mirrored

On the basis of the presumed weighting of allocentric and egocentric contributions to spatial haptic matching tasks, further predictions can be made. First, tasks that lead to different outcomes when performed in either an allocentric reference frame or an egocentric reference frame, should lead to large deviations from veridical (physically correct) when participants are instructed to perform the task in an allocentric way. The parallel matching task is a clear example of such a task if performed in a condition where the reference frames are far from being aligned. Likewise, making two bars perpendicular to each other should lead to similar deviations as in the parallel matching task since the difference in the alignment of the reference frames is the same. The second prediction is that if performance in either an allocentric or an egocentric reference frame would lead to the same outcome, deviations should be small and not systematic. An example of such a task is mirroring the orientation of a reference bar in the midsagittal plane.

Kappers (2004) asked nine participants to perform these three tasks. The set-up was the same as illustrated in Figure 1a. The two locations for reference and test bars were far apart to maximize the disalignment of the ego- and allocentric reference frames. The reference bar appeared in pseudorandom fashion either on the left or on the right side and the test bar was presented at the opposite location. Reference orientations were 0°, 45°, 90°, and 135°, and all combinations of task, orientation, and location of reference bar were repeated three times. Participants were instructed to perform the tasks bimanually.

Overall deviations for the parallel, perpendicular, and mirrors tasks were 37°, 36°, and 2°, respectively. Clearly, the parallel task and the perpendicular task lead to the same deviations, whereas the mirroring task can be performed almost veridically. Also in these tasks, performance was participant-dependent. However, the deviations obtained in the parallel task highly correlated with those of the perpendicular task, whereas none of them correlated with the mirroring deviations (Kappers, 2004).

### Reversal of Oblique Effect

In both the haptic and the visual literature, "oblique

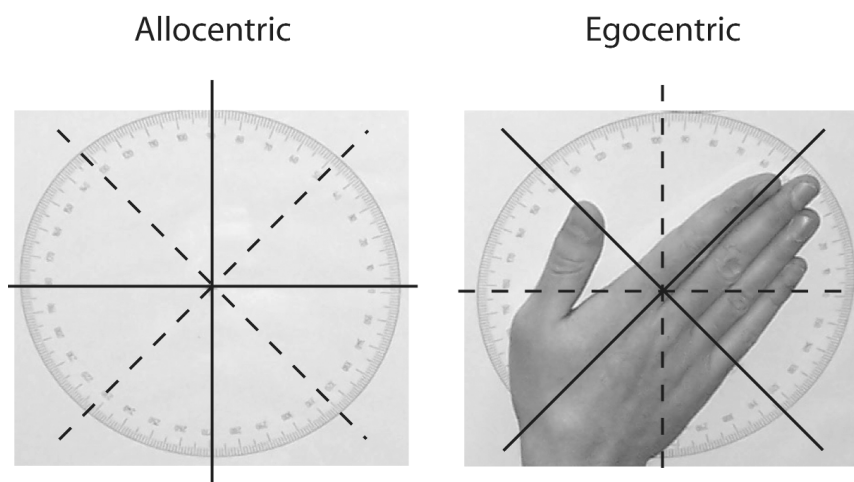Allocentric                                    Egocentric

*Figure 5.* Illustration of cardinal (solid lines) and oblique (dashed lines) orientations in allocentric and egocentric reference frames.
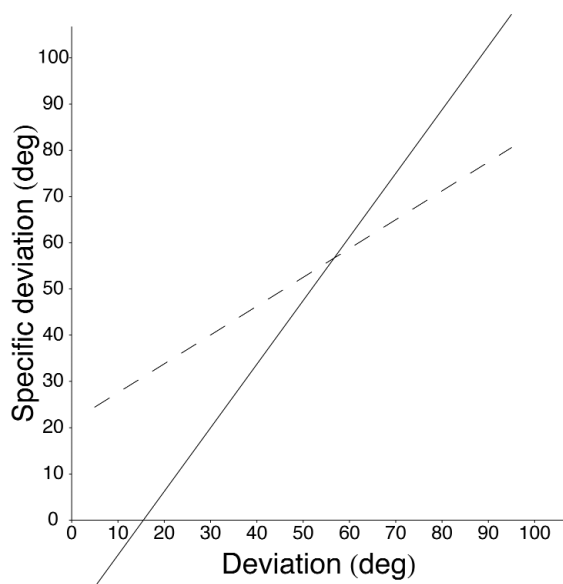


*Figure 6.* The solid (dashed) line represents a fit through the deviations due to cardinal (oblique) reference orientations of 68 participants. For clarity, the individual data points (2 * 68) are omitted. In this experimental condition, participants were observed to generally place their hands in oblique orientations (see Figure 5).

effects" are often reported (e.g. Appelle & Countryman, 1986; Appelle & Gravetter, 1985; Gentaz & Hatwell, 1995; Lechelt, Elluk, & Tanne, 1976; Lechelt & Verenka, 1980). In most of these studies, the oblique effect concerns the larger spread in measurements for oblique orientations of a stimulus as compared to cardinal orientations. In the parallelilty experiments, however, the oblique effect manifests itself most clearly in differences in signed deviations between cardinal and

oblique orientations (Kappers, 2003, Kappers & Viergever, 2006).

"Oblique" and "cardinal" are defined with respect to a reference frame, and as a consequence, they are not necessarily the same for allocentric and egocentric reference frames. An example is given in Figure 5 where the hand-centred egocentric reference frame is rotated 45° clockwise with respect to the allocentric reference frame. An oblique effect in the allocentric reference frame will consist of larger deviations for 45° and 135° orientations. However, these orientations will be cardinal orientations in the hand-centred egocentric reference frame, as they are aligned with or perpendicular to the hand (see Figure 5); therefore, in such an egocentric reference frame, the oblique effect will be reversed when expressed in allocentric coordinates.

This oblique effect leads to interesting predictions. According to the weighted average model, participants with large deviations in the parallelity task rely more on an egocentric reference frame than on an allocentric reference frame; for participants with only small deviations, this is opposite. As a consequence, for participants with large egocentric weighting factors, an oblique effect will mainly occur in the egocentric reference frame and therefore show up as a reversed oblique effect in allocentric space. This is exactly what was tested by Kappers (2003). In this study, 68 participants did a number of trials for both cardinal and oblique reference orientations in the experimental configuration shown in Figure 1a. Using the least mean squares method, lines were fitted through the average cardinal and oblique deviations. These lines are shown in Figure 6 (for clarity, the 126 data points are omitted). For participants with on average relatively small deviations (less than 57°), a normal oblique effect can be
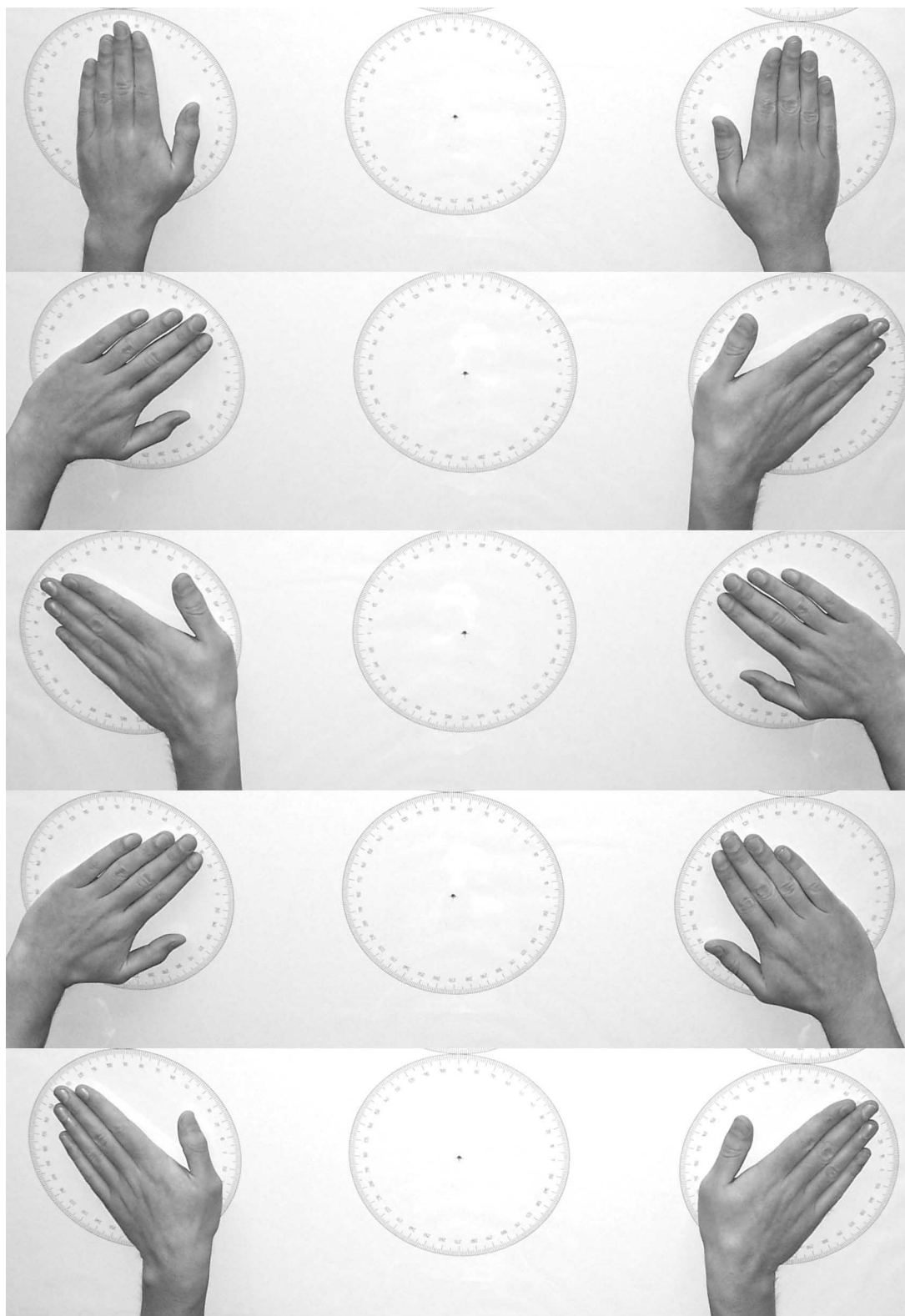
*Figure 7.* Conditions: Normal, Oblique 45°, Oblique 135°, Convergent, Divergent.

observed: Deviations for oblique reference orientations are larger than those for cardinal reference orientations. However, for participants with large average deviations, the more egocentric participants, the oblique effect reverses, just as predicted. These findings are replicated by Kappers (2004) and Kappers and Viergever (2006) for the horizontal plane, and also found by Hermens, Kappers, and Gielen (2006) and Volcic, Kappers, and Koenderink (2007) for the frontoparallel plane.

### Influence of Hand Orientation

If the egocentric reference frame that biases performance in parallelity matching is hand-centred, then the interesting consequence must be that the deviations can be increased or decreased by manipulating hand orientation. If, in an experiment, the locations of reference and test bars are kept constant, then the allocentric reference frame also remains constant over conditions. Thus, if deviations vary as a result of hand orientation, a hand-centred egocentric reference frame has to be involved in performance of that task. Kappers and Viergever (2006) instructed 12 blindfolded participants to perform parallel matching while keeping their hands in specified orientations. Participants had to rotate the test bar by making small hand movements such that the orientation of their hands remained within a few degrees of the specified orientation. For each trial, the experimenter checked whether the participant fulfilled this requirement. Again, the reference orientations were 0°, 45°, 90°, and 135°, which were repeated three times for reference bars both at the left and right sides of the set-up.

Five different conditions were measured, as shown in Figure 7. In the Normal condition (upper picture), both hands had to be kept straight forward. This condition serves as a baseline since allocentric and hand-centred egocentric reference frames are aligned. In the Oblique-45 and Oblique-135 conditions (second and third pictures from top), the hands are again aligned with each other, but rotated with respect to the allocentric reference frame. However, since this rotation is the same for both hands, this should not lead to a change in deviation size. The model predicts deviations similar to those in the Normal condition. In the fourth condition, the hands converge toward each other. They are not aligned with each other, nor with the allocentric reference frame. Given the direction of rotation, the model predicts signed deviations that are smaller relative to Normal. Finally, in the Divergent condition (bottom picture), the hands are rotated outwards. Again, the hands are not aligned with each other nor with the allocentric reference frames, so for this condition the model predicts larger signed deviations relative to Normal.

The average deviations for these five conditions were 19°, 18°, 17°, -2°, and 32°, respectively. First of all, it should be noted that the deviations indeed vary over the conditions as predicted. Thus, it is clear that a hand-centred reference frame plays a decisive role in the perception of haptic parallelity. However, it should also be noted that the deviations in the Normal condition are not so small as one should expect if only a hand-centred reference frame would be involved, because in the Normal condition, the hand-centred reference frame and the allocentric reference frame are aligned. Kappers and Viergever (2006) discuss a number of possible explanations, one of which is the additional influence of a body-centred reference frame.

### Discussion

The experiments described in this paper all show distinct evidence that perceptual judgments in the parallelity task are based on input from both egocentric and allocentric reference frames. Other independent studies have replicated the deviations in the horizontal plane (e.g., Kaas & Van Mier, 2006; Newport, Rabb, & Jackson, 2002). The conclusion, however, is not confined to this horizontal plane, as similar findings were reported for the midsagittal plane (Kappers, 2002 – Figure 1c), the frontoparallel plane (Hermens et al., 2006; Volcic et al., 2007 – Figure 1c) and even in three-dimensional space (Volcic & Kappers, 2006).

How much the ego- and allocentric reference frames each contribute depends on the participant. However, various studies have shown that the weighting of the contributions of the ego- and allocentric reference frames may also be manipulated by the experimental conditions. Newport et al. (2002), for example, also performed parallelity experiments on a horizontal set-up. In one condition, participants were blindfolded; in another condition, participants were allowed to look around, although their hands and the set-up were blocked from their view. In both conditions, systematic deviations were obtained, but these were significantly smaller in the latter condition. Similar results were obtained by Zuidhoek, Visser, Bredero, & Postma (2004). The explanation they provide is that vision, even when noninformative for the task, provides sensory awareness for a more allocentric reference frame. In other words, the weighting factor for the egocentric reference frames becomes significantly smaller.

In a variant of the parallelity task, Zuidhoek, Kappers, Van der Lubbe, and Postma (2003) introduced a 10-s delay between exploration of the reference bar and matching of the test bar, which resulted in significantly smaller deviations than in the nondelay condition. For a different experimental situation, Rosetti, Gaunet, and Thinus-Blanc (1996) have argued that a

delay induces a shift from an egocentric towards a more allocentric reference frame. Zuidhoek et al. (2003) concluded that the same argument applies to their own findings. So again, the weighting factor for the egocentric reference frames becomes smaller.

Support for the conclusion that both allocentric and egocentric reference frames play a role in the perception of parallellity is quite convincing. More equivocal is the answer to the question as to which egocentric reference frame is of major importance. In most experiments, the contributions of hand-centred and body-centred reference frames cannot be distinguished, as in most cases they are aligned with each other. The experiment in which hand orientation was varied in various experimental conditions (Kappers & Viergever, 2006) showed that rotating the hands directly influenced the size of the deviations in the predicted manner. This finding argues in favour of a hand-centred reference frame as the major constituent of the model. Also, the model fits show a preference for a hand-centred egocentric reference frame as compared to an allocentric reference frame. However, in the experimental condition of Kappers and Viergever (2006), where the hand-centred and allocentric reference frames were aligned (the Normal condition), still significant deviations were found that cannot be explained by the hand-centred reference frame. Kappers and Viergever discuss a number of possibilities. One is the additional influence of a body-centred reference frame. Given the good fit shown in Figure 4c (right), this is indeed a likely possibility. In that case, the deviations would be determined by a weighted average of contributions from three reference frames, one allocentric and two egocentric. Current information is not sufficient to decide on the relative contributions of the two egocentric reference frames.

One remaining issue needs to be discussed and that concerns the nature of the allocentric reference frame. So far, the allocentric reference frame has been treated as if it is identical to a physical reference frame outside the participant. This is in line with a definition given by Klatzky (1998) that in an allocentric reference frame points are located within a framework external to the holder of the representation and independent of his or her position. However, even though the allocentric reference frame is anchored in external space, it can only be taken into account through the participant's perceptions. As suggested by, among others, Milner and Goodale (1995), egocentric and allocentric information is processed in different brain areas, at least for vision. Therefore, the current parallellity paradigm may shed new light on the neuropsychological mechanisms of haptic spatial processing.

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