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Egocentric reference frame bias in the palmar haptic perception of surface orientation

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Abstract

The effect of egocentric reference frames on palmar haptic perception of orientation was investigated in vertically-separated locations in a sagittal plane. Reference stimuli to be haptically-matched were either presented haptically (to the contralateral hand) or visually. As with prior investigations of haptic orientation perception, a strong egocentric bias was found such that haptic orientation matches made in the lower part of personal space were much lower (i.e., perceived as higher) than those made at eye level. The same haptic bias was observed when the reference surface to be matched was observed visually as was observed for bimanual matching. These findings support the conclusion that, despite the presence of an unambiguous allocentric (gravitational) reference frame in vertical planes, haptic orientation perception in the sagittal plane reflects an egocentric bias.

Perception by means of haptic exploration allows us access to the spatial layout of surfaces near our bodies (i.e., peri-personal space). However, although people may be able to navigate the world successfully, haptic perception does not generally demonstrate an accurate reflection of physical reality. In particular the haptic perception of orientation is subject to biases that suggest an egocentric reference frame strongly influences haptic perception (Kappers, 1999, 2004; Volcic & Kappers, 2008). Orientation judgments must always be made relative to some reference frame or other (e.g., perceived vertical or horizontal). In principle, perceived orientation in a horizontal plane is most easily referenced to the straight-ahead defined by the body, but orientations in vertical planes, such as the sagittal plane, can be referenced to the allocentric reference frame defined by the force of gravity.

Kappers (1999, 2004) showed that when participants made haptic judgments of parallelism in a horizontal plane, they used a combination of egocentric and allocentric reference frames, such that, for example, in the space to the right of the body's midline, physical orientations that were splayed out to the right were felt to be more rotated to the left than they were (compared to a parallel orientation presented at midline or to the left of midline). This bias was qualitatively consistent with a bias toward a representation of the surface orientation relative to the outstretched limb: For a limb stretched to the right, a horizontal

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rod in a plane sagittal to the body, would be tilted to the left relative to the main axis of the limb. The converse would be true on the left.

Kappers (2002; see also Gentaz & Hatwell, 1995, 1996) demonstrated a similar type of egocentric haptic bias in a vertical plane (the mid-sagittal plane) using rods at different vertical positions that were felt by seated participants. The rods were to be set parallel to one another. Analogous to the horizontal (table-top) case, rods in lower positions were felt to be oriented in a way that reflected the contribution of a body-centric or limb-centric bias: Lower rods were felt to be parallel with higher rods when the lower rod had a lower orientation such that, rather than being physically parallel, the two rods actually converged at the ends nearer to the participant. It is worth noting that, although this latter demonstration was conducted in the mid-sagittal plane (i.e., a vertical plane; see also Volcic, Kappers & Koenderink, 2007), rather than in a horizontal plane, the type of wrist movement studied was still in the lateral plane in relation to the arm, as illustrated in the left side of Figure 1. That is, adjusting the orientations of rods on a table surface or on a mid-sagittal vertical surface normally involves abduction of the wrist (movement toward the thumb) and adduction (movement toward the outside of the hand), while the hand stays in the same plane relative to the arm throughout the motion. Perhaps the effects of egocentric reference frames carried over from the horizontal case to the vertical case because the joint used was the same.

That is, despite the vertical orientation of the allocentric plane investigated by Kappers (2002), the egocentric bias that was demonstrated involved the same proprioceptive reference axis (lateral to the wrist) as in her more extensive studies of orientation biases in the horizontal plane. In contrast, there have not been published studies of vertical location-based biases that might be associated with the counterpart of this type of wrist motion, that is, palmar flexion of the wrist (moving down toward the palm) and dorsi-flexion or extension of the wrist (tilting up toward the back of the hand). Demonstrating such a bias would help show that that Kappers' observations apply to haptic perception of orientation in vertical planes, generally, rather than only haptic perception involving lateral wrist movements. Volcic and Kappers (2008) have studied haptically perceived co-planarity using an array of rods that may have been explored with palmer actions. Coplanarity is an important form of haptic parallelism, but provides only limited information about possible effects on haptic perception of changing the vertical location of exploration in the sagittal plane.

Moreover, Kappers (2002) observed that the bias in the haptically perceived orientation in a vertical plane seemed to be smaller when a single hand was used to feel two different surfaces (in succession) rather than when the orientations of two hands were compared. Although Kappers suggested that this might be due to allocentric demands of memory representations, it is also possible that bimanual haptic comparison encourages focus on more peripheral sensory information (such as joint orientations) rather than the on the allocentric spatial perception of orientation. Similar considerations may apply to judgments of coplanarity. Therefore, to help test whether there is an egocentric haptic bias in perceived orientation within a vertical plane, we sought to test whether evidence of an egocentric haptic reference frame would persist even when the reference surface was not experienced haptically. That is, in addition to bimanual matching, we also tested for effects of egocentric reference frames on (cross-modal) haptic orientation matching to visual reference surfaces.

Our experiments therefore seek to further investigate Kappers' (2002) report of an egocentric bias in haptic perception in a vertical plane by testing whether this bias generalizes to dorsal/palmar motion of the wrist in a sagittal plane and to cross-modal orientation matching. In order to test for evidence of egocentric reference-frame effects on palmar haptic perception, we used palm boards (see Figure 2) located at the subjects' eye level and navel level with axes of rotation that were perpendicular to the sagittal plane of the participant. In Experiment 1, our task was entirely haptic, with blind-folded participants matching the slopes of a static reference board felt with the left hand by means of a haptic surface (a palm-board) adjusted by the right hand. In Experiment 2 participants observed the reference orientation visually and tried to match it with a haptically-perceived orientation of a palm board either at a high or a low vertical position in personal space.

To anticipate, even when dorsal/palmar flexion of the wrist is involved, haptic orientation matching of perceived orientation within a vertical plane shows strong egocentric biases such that haptic orientations feel steeper (and haptic matches are therefore set lower) when they are produced in a lower part of space than when they are produced in a higher part of space despite that orientation in a vertical plane has a natural allocentric reference frame defined by gravity.

Experiment 1: Bimanual matching of perceived orientation in vertical planes

In this experiment we tested the effect of haptic stimulus height on haptically-experienced surface orientation in surface pitch (orientation in a vertical plane).

Method

Participants—Twelve undergraduate students (8 female) at Swarthmore College, naïve to the hypothesis, participated in exchange for course credit. Experimental procedures for both experiments 1 and 2 were approved by the local ethics committee, and all participants gave informed consent.

Design—In each of two blocks of trials, seven fixed reference orientations (12, 18, 24, 30, 36, 42, and 48° from horizontal) were presented to the left hand of a blindfolded observer in random order at a fixed height and matched by haptic adjustment of a low-friction palm board by the right hand of the observer. Only a single trial was used at each orientation because our interest was in measuring bias rather than precision. The height of the axis of rotation of the matching surface was varied between blocks of trials, and the order was counterbalanced between observers. The height of the center of the reference surface was fixed at 1.35 m. The height of the center of the adjustable haptic surface, while scaled to the observers' bodies, was always either above the reference surface (set at the measured eye-level of each participant, $M = 1.61$ m) or below the reference surface (set at the level of the navel of each participant: $M = 1.02$ m).

Materials and procedure—The reference stimulus was a flat wooden surface with uneven, rounded edges, approximately 35cm wide and tall. The surface was painted with a clear lacquer so that it was smooth to the touch. Subjects were blindfolded with a plush sleep mask throughout the procedure. On each trial they placed their left-hand on the reference board (set at one of seven fixed pitch orientations), and their right hand on an adjustable surface (palm board), which consisted of a wooden surface that could be rotated freely in pitch. Participants were instructed to set the palm board at a slant parallel to the reference stimulus, while touching both at the same time. They stood slightly less than an arm's distance away from the boards, and in a position midway between the reference and palm boards, which were placed about 10 cm apart. A protractor attached to the palm boards allowed the experimenter to record the angle to which the subject set the board on each trial.

Participants were first measured to determine overall height, eye-height, and navel height (participants placed their finger at their navel and the height of this position was recorded). The palm boards, which rotated at an axis 1 cm below their surfaces were set so that they were at the required height when level. Participants were then blindfolded and performed a block of 7 trials with a palm board at the height of their navels, and a block of seven trials with a palm board at eye height. To avoid anchoring effects, the palm board orientation was not reset between trials, but participants were instructed to remove their hands from both the palm and reference boards while the reference board was reset.

Results and Discussion

Mean matches are shown in Figure 3 for each of the two palm board heights. Limb-or ego-centric coding predicts that the palm board should be set too low in the lower position and too high in the higher position. Because the gains (mean slope of each participant's data) of the slant functions did not differ reliably from each other, $t(11) = 1.54$, $p = .15$, nor did either gain differ reliably from 1.0 (high position: M = 1.02, $t(11) = 0.22$, $p = .83$; low position: M = 0.89, $t(11) = 1.29$, $p = .22$), we computed the mean signed error for each participant at each test position and used this to test for the differences between position as evidence of egocentric bias.

As expected, settings were reliably lower in the low palm board position (M = −9.6°) than in the high palm board position (M = 4.4°), $t(11) = 6.31$, $p < .0001$, *ES* (M/SD) = 1.9. Moreover, estimates in the low palm board position were reliably lower than the reference orientation, $t(11) = 5.38$, $p = .0002$, *ES* = 1.6. Estimates in the eye-height palm board condition were marginally higher than the reference orientation, $t(11) = 2.04$, $p = .0660$, *ES* = 0.6.

The magnitude of the effect we observed is similar to that reported by Kappers (2002). Kappers tested four reference orientations, all of which were either cardinal orientations (horizontal and vertical) or the two oblique orientations midway between. We tested 7 different oblique orientations. Nonetheless, quantitatively, our results are similar to her results under similar conditions. We can make this comparison for her subject NK, for which complete data were shown (Kappers, 2002, Fig. 2). For matches to a fixed reference of 45° explored by the left hand, matches made with the right hand at locations 2 and 4 in her design, which were separated vertically by 40 cm, differed by 11°. In our experiment, the average vertical separation between eye-level and navel level matching locations was 59 cm and the average deviation between high and low matches to haptic references of 42° and 48° was 14°, which is proportionally similar to the size of effect observed by Kappers using a rather different procedure.

Our observations thus confirm that haptic orientation matching by means of wrist flexion and extension involves similar substantial biases consistent with partial egocentric coding of haptic orientation perception in a vertical plane. (Pure egocentric coding would predict total differences greater than 45°). When the forearm was oriented downward, settings were significantly lower than then the forearm was oriented upward.

Experiment 2: Cross-modal matching of orientation in a vertical plane

Experiment 1 employed bimanual comparison. Kappers (2002) found greater egocentric bias in the bimanual case than in her unimanual version of the experiment. A unimanual haptic matching task requires successive comparison and Kappers suggested that this memory requirement may have increased dependence on allocentric frames. It is also possible that the converse is true and that bimanual comparison encourages dependence on more peripheral, egocentric comparisons of felt limb postures (e.g., dorsiflexion of the wrist) rather than allocentric haptic spatial perception. A neutral approach to test this second alternative is to use a visual reference surface rather than a haptic one so that haptic judgments of palmar orientation in a vertical plane can be unimanual but not successive. That is, comparison between a visual surface and a haptic one cannot be made based on the comparison of peripheral limb postures of the two limbs since only one limb is employed. We therefore repeated Experiment 1 using a visual reference surface.

Method

Participants—Fifteen undergraduate students (9 female) at Swarthmore College, naïve to the hypothesis, participated in exchange for monetary compensation. None had participated in Experiment 1.

Visual stimulus—The same wooden reference surface was used as in Experiment 1. The pronounced visual grain of the wood was clearly visible.

Procedure—The same design, materials and procedure as in Experiment 1 were used, but the reference surface was inspected visually instead of haptically. Participants wore restricting goggles (used for pilot training; see Figure 2) so that the palm boards could not be seen when inspecting the visual surface. A piece of foam-core was additionally mounted vertically on the side of the palm board apparatus to prevent visual observation of the hand and palm board. Between trials, while the reference surface orientation was being changed, participants were required to look at their feet.

Results and Discussion

Mean matches to visually-observed surface orientations are shown in Figure 4 for each of the two palm board heights. As in Experiment 1, the mean gains did not differ reliably from 1.0 in either palm board position (high position: M = 1.10, $t(14) = 1.54$, $p = .15$; low position: M = 0.94, $t(14) = 0.84$, $p = .42$). There was evidence that they differed from each other, $t(14) = 2.26$, p = .0402. T-tests comparing the mean signed errors in each position confirmed that settings were reliably lower in the low palm board position (M = − 4.6°) than in the high palm board position (M = 7.5°), $t(14) = 5.56$, $p < .0001$, *ES* = 1.5. Estimates in the low palm board position were reliably lower than the reference orientation, $t(14) = 2.87$, $p = .0124$, *ES* = 0.8, and estimates in the eye-height palm board condition were reliably higher than the reference orientation, $t(14) = 4.08$, $p = .0011$, *ES* = 1.1.

In Experiment 1 we maintained the haptic reference surfaces at a constant height and measured differences of about 14° in matched orientation between the high and low palm board locations. In Experiment 2 we again maintained the visual reference surfaces at this same height and measured similar overall differences (12°) between different haptic matching positions. The magnitude of the measured haptic bias in this experiment did not differ reliably from that observed in Experiment 1, $t(25) = 0.61$, $p = .5481$. This confirms that haptic matches in Experiment 1 reflect real haptic spatial perceptual biases. That is, the biases found in the bimanual haptic case studied in Experiment 1 do not simply reflect peripheral matching of felt limb posture when comparing surfaces at different heights, because they are also found when the reference surface is observed visually rather than haptically. Thus, the egocentric bias in perceived haptic orientation occurs even in contexts requiring cross-modal matching as well as a natural allocentric (gravitational) reference frame.

Any absolute differences in the haptic vs. visual perception of the reference surface orientations is not of direct theoretical interest to the present investigation; however overall matches were marginally lower (by about 3.6°) in Experiment 2 than in Experiment 1, $t(25) = 1.92$, $p = .066$. If the haptic reference surface had been lower, the resulting matches might have been even more similar. For example, by assuming a linear effect of height, and dividing the 14° of difference found in Experiment 1 by the mean 59 cm of vertical separation, we can estimate that lowering the haptic reference by 15 cm (i.e., to a height of 120 cm) would have raised the haptic matches by 3.6°. (This height would represent 70% of the full measured height of the participants in Experiment 1 – or about chest level.) In principle, such a height should have made the haptic judgments to the haptic reference quite similar to those made to the visual reference surface and may account for the excellent correspondence between visual and haptic surface orientation perception reported by Durgin and Li (2012) using haptic orientation perception at chest level.

General Discussion

Despite the presence of an allocentric gravitational reference frame for orientations in vertical planes, Experiments 1 and 2 show that an egocentric bias in haptic perception is a pervasive phenomenon in the sagittal plane as well as the horizontal plane. Although people sometimes assume that haptic perception is more accurate or reliable than visual perception, our data confirm that haptic perception of orientation is susceptible to systematic spatial bias and show that this bias occurs in the sagittal plane even for cross-modal matching. Gravity provides a natural allocentric reference frame for orientations in vertical planes that is not present for orientations in a horizontal plane, but the human haptic system retains an egocentric bias nonetheless.

By adding visuo-manual comparison in Experiment 2, we have shown that the bimanual case appears quite similar to the visuo-manual case. Both involve simultaneous comparison, but the visuo-manual case is far less susceptible to an interpretation that depends on peripheral matching. Kappers (2002) found less bias with unimanual matching, which she suggested might be an effect of memory requiring an allocentric reference frame. However, crossmodal matching probably also encourages allocentric coding, so it may be that another explanation is needed. It is possible that unimanual comparison achieved better haptic orientation constancy in her study by taking advantage of gravitational information made available during active limb re-positioning.

In contrast to these findings with haptic perception, a recent study of visual surface orientation perception reported good location constancy (Durgin, Li & Hajnal, 2010). Using verbal report of visually-observed wooden surfaces, like those studied here, they found essentially no effect when surface height was varied between eye level and mid-torso level, despite that the lower surfaces were viewed with gaze declined by about 40°. Sedgwick and Levy (1985) similarly concluded that visual experience was primarily of allocentric rather than egocentric surface orientation. For visual surface matching in near space, haptic measures have been argued to be less accurate (i.e., providing lower estimates) than gesturing with a free hand (Durgin, Hajnal, Li, Tonge & Stigliani, 2010). However, that study employed a waist-high palm board. The present study shows that the waist-high palm board may have contributed to the lowered palm board setting they observed. This is consistent with their concern that palm boards used in such a posture as measures of perceived visual surface orientation may misrepresent the perceptual experience of participants.

Reference frames are fundamental to the encoding of orientation (Kappers, 2004; Luyat, Gentaz, Corte & Guerraz, 2001; Palmer, 1989; Rock, 1990; Volcic et al., 2007). Here we have replicated the observation that egocentric reference frames produce strong biases on haptic orientation perception even in the sagittal plane, where allocentric (gravitational) reference frames might well be expected to dominate egocentric reference frames. Moreover, we have extended this observation in two ways. First, we showed that the previously-uninvestigated haptic posture requiring dorsal/palmar wrist flexion shows this bias in the same way as has previously been shown for the posture requiring abduction/adduction of the wrist. Second, we showed that the haptic bias is also present in a cross-modal situation where haptic perception is matched to a reference orientation that is observed visually. These observations help to further establish that dependence on egocentric reference frames seems to be a general bias of haptic spatial perception, even in a vertical plane, rather than an artifact of haptic-haptic matching or of one particular haptic posture.

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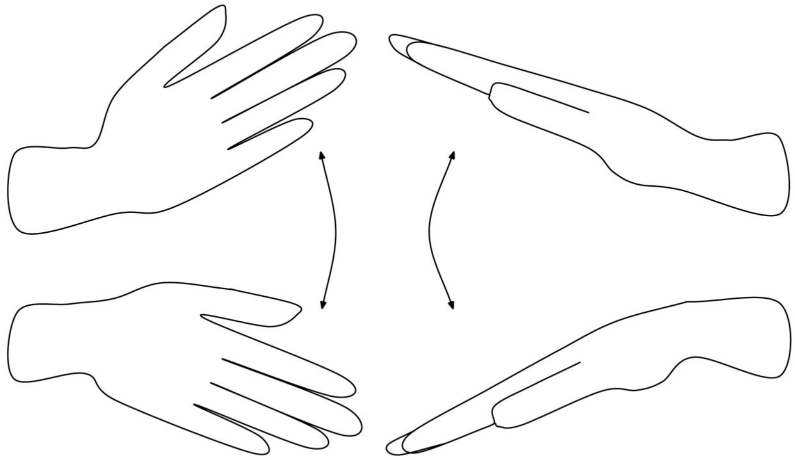

Figure 1.

Wrist flexion can be lateral to the forearm (left) either as radial flexion (abduction, top) or as ulnar flexion (adduction, bottom). Alternatively, wrist flexion can be dorsal/palmar to the forearm (right) either as dorsal flexion (extension, top) or as palmar flexion (flexion, bottom).

Figure 2.
A model demonstrating, left to right, (1) the slant apparatus with the palm board in the low (navel-height) position and (2) high (eye-level) position for haptic matching, (3) the visual reference (low palm board) condition of Experiment 2 and (4) a front view of the visual restrictor goggle used in Experiment 2. Note that an additional visual barrier (not shown here) was attached to the left face of the palm board mount in Experiment 2 so as to fully occlude the hand from possible view.

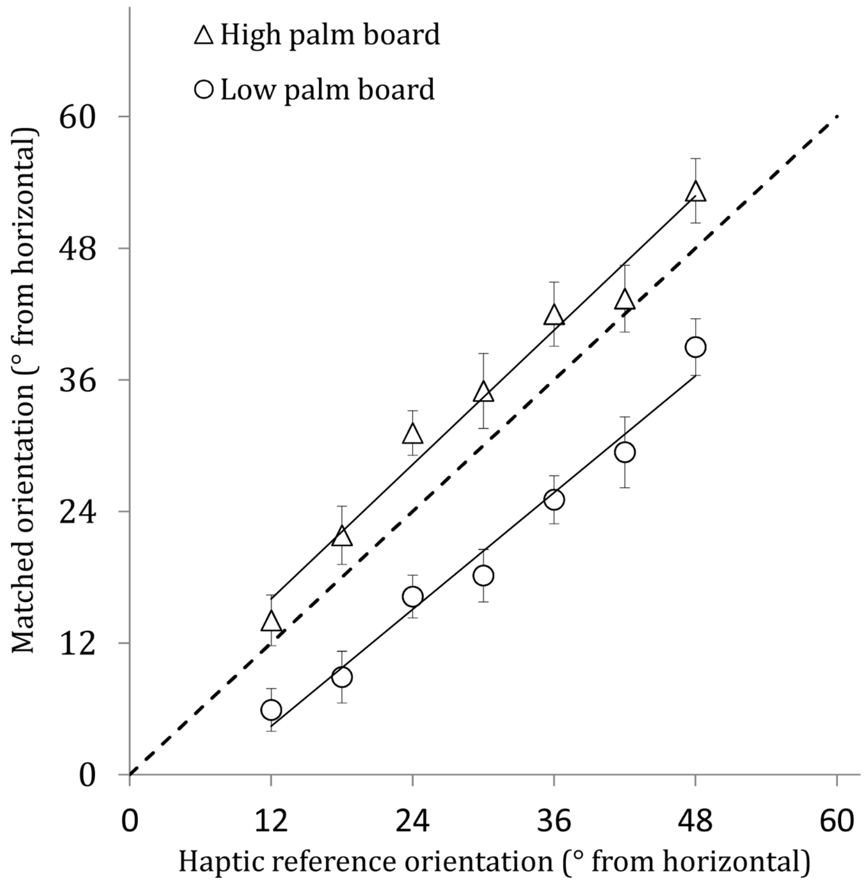

Figure 3.
Matched haptic orientation in Experiment 1 (haptic reference) as a function of reference orientation and palm board height. Orientations are all relative to horizontal, and are positive when the farther end of the surface is elevated relative to end near the observer. Standard errors of the means are shown.

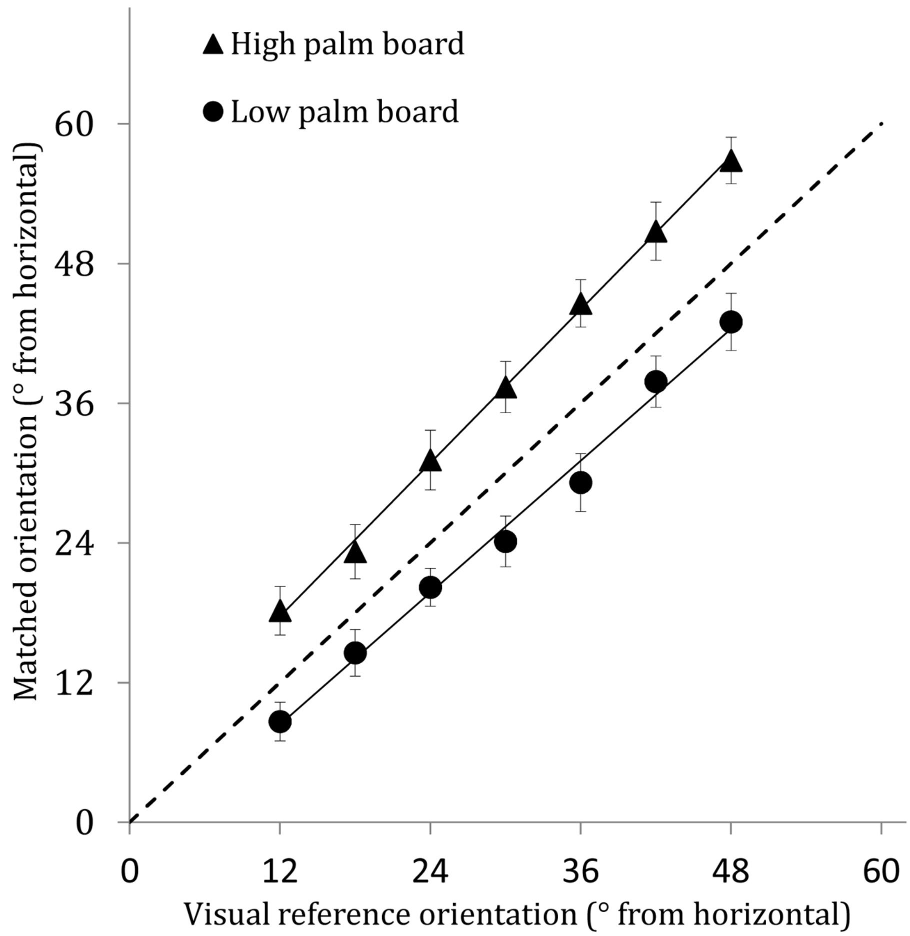

Figure 4.

Matched haptic orientation in Experiment 2 (visual reference) as a function of reference orientation and palm board height. Standard errors of the means are shown.