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# Judgments of reachability are independent of visuomotor adaptation

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**Abstract.** The furthest distance that is judged to be reachable can change after participants have used a tool or if they are led to misjudge the position of their hand. Here we investigated how judged reachability changed when visual feedback about the hand was shifted. We hoped to distinguish between various ways in which visuomotor adaptation could influence judged reachability. Participants had to judge whether they could reach a virtual cube without actually doing so. They indicated whether they could reach this virtual cube by moving their hand. During these hand movements, visual feedback about the position of the hand was shifted in depth, either away from or toward the participant. Participants always adapted to the shifted feedback. In a session in which the hand movements in the presence of visual feedback were mainly in depth, perceived reachability shifted in accordance with the feedback (more distant cubes were judged to be reachable when feedback was shifted further away). In a second session in which the hand movements in the presence of visual feedback were mainly sideways, for some participants perceived reachability shifted in the opposite direction than we expected. The shift in perceived reachability was not correlated with the adaptation to the shift in visual feedback. We conclude that reachability judgments are not directly related to visuomotor adaptation.

## 1 Introduction
If one wants to grasp an object, one can easily estimate whether a movement of the arm is sufficient or whether one needs to walk toward the object before being able to grasp it. This suggests that people can judge what is within reach. A common finding in studies on perceived reachability is that participants tend to overestimate reachability at midline positions: participants think they can reach an object which they cannot (Bootsma et al 1992; Carello et al 1989; Heft 1993; Mark et al 1997). This has been explained as participants not being able to account for the constraints of the experimental setup when performing the task, for example not being able to consider the restriction of the range of motion that arises from strapping the trunk to the chair. This phenomenon is known as 'whole body engagement' (Rochat and Wraga 1997). Another explanation for participants overestimating reachability is that the experiments are usually conducted in impoverished visual conditions (Coello 2005; Coello and Iwanow 2006). Targets in an untextured black context are often perceived to be closer than they really are (Coello and Magne 2000; Foley 1968; Norman et al 1996), which will obviously lead to an overestimation of the range of distances that are judged to be within reach.

One clear case in which the range of distances that are judged to be within reach is extended is during tool use (eg when using a stick or a rake). Participants then judge objects to be closer than when no tool is used (Witt et al 2005; but see de Grave et al 2011). This suggests that tool-use expands the representation of the participant's limb so that it encompasses the entire tool (Ackroyd et al 2002; Berti and Frassinetti 2000; Pegna et al 2001) or at least encompasses the end-effector (Collins et al 2008; Holmes et al 2004, 2007; reviewed in Higuchi et al 2006 and in Holmes and Spence 2004). The presence of a tool does not always change the borders of reachable space.

For example, a stick lying on the table without a physical connection to the hand (Maravita et al 2001) or passively holding a stick or rake (Farnè et al 2005a, 2005b; Witt et al 2005) do not change the borders of what is perceived to be reachable space. The latter findings imply that active use of the tool is required to consider objects that are beyond reach to be within reach. However, active use is not always enough. Active pointing with a laser pointer does not produce a shift in reachable space (Berti and Frassinetti 2000; Gamberini et al 2008; Longo and Lourenco 2006), probably because there is no straightforward mechanical connection between the hand and the endpoint of the laser beam.

The boundaries of reachable space may also be changed by influencing where one judges one's own hand to be (Holmes and Spence 2004). When a rubber hand is placed at a position that is slightly shifted from a participant's hand, visual stimulation of the rubber hand, coupled with tactile stimulation of the participant's own invisible hand, induces the illusory feeling that the visible rubber hand is the participant's own hand (Botvinick and Cohen 1998). When asked to indicate the position of the (rubber) hand with their contralateral hand, participants indicate a position somewhere between the seen position of the rubber hand and the felt position of their own hand. The fact that people combine the seen and felt positions of the hand to judge where their hand is in space suggests that shifting visual feedback about the position of the hand will shift judgments of reachability.

Here, we investigate whether this is so, and to what extent shifts in the perceived position of one's hand can account for the shifts in the range of distances that are considered to be within reach. In two blocks of reachability judgment trials, we asked participants whether they were able to touch a stimulus in a virtual environment without actually doing so. In both blocks, a virtual image provided visual feedback about the location of the hand during goal-directed movements. In one block, the virtual image was shifted slightly away from the participant. In the other block, it was shifted towards the participant. In both blocks, we also tested the state of visuomotor adaptation in position trials.

There are various possible mechanisms by which the shifting feedback about the position of the hand could affect judgments of reachability. A possibility that is consistent with combining vision and proprioception to judge the position of the hand, as mentioned above, is that the extent to which the arm can be extended further than its current position is judged from the felt posture alone, whereas its current position is estimated from a combination of the seen and felt positions. Consequently, if the hand is seen to be further away, one will overestimate how far one can reach. Another possibility is that haptic feedback is used to calibrate visually perceived distance. In both cases we expect to find the same judgment errors when aligning the unseen hand with a visually presented target as when judging reachability, but in the former only the hand used for the task is affected, whereas in the latter the hand that is used for the task is irrelevant (because vision has been changed).

However, shifting feedback about the position of the hand need not affect judgments of reachability to the same extent as judgments of hand position. For instance, if visual feedback is used to calibrate the haptically perceived joint angles, providing shifted feedback will lead to the orientation of the arm being misjudged, but its judged length when extended will not change. If the judged dimensions of limb segments are affected (for instance to encompass a tool), rather than the judged angles between them, judgments of reachability may be affected, but only if the change in dimensions consists (partly) of lengthening/shortening of the segments. To what extent this will be the case depends on the posture of the arm at the time that the feedback is provided. Various manipulations in the experiment were designed to distinguish between these and similar mechanisms. All mechanisms have a common prediction: there will be a correlation between the visuomotor adaptation and the change in perceived reachability.

## 2 Method

### 2.1 *Participants*

Six participants took part in the two sessions of this study. All participants had normal or corrected-to-normal vision and were right-handed by self-report. The study was part of a programme that has been approved by the ethics committee of the Faculty of Human Movement Science.

### 2.2 *Stimuli and apparatus*

Participants sat in a dark room on a height-adjustable stool in front of two mirrors in which they saw virtual stimuli. The three-dimensional virtual environment was created by presenting different images to the left and the right eye using a combination of two CRT monitors and two mirrors (figure 1). The imaginary line that protruded from a position between the eyes and was tilted 30° downward from eye-height will be referred to as the $z$-axis. In their right hand participants held a physical cube (5 cm × 5 cm × 5 cm) that they could feel but not see. The location of this cube was tracked with an Optotrak 3020 system (sampling rate 250 Hz, resolution 0.01 mm). A (yellow) virtual image of the physical cube provided feedback about the position of the physical cube that participants were holding in their hand. In the second session, participants also held a second, identical physical cube in their left hand. They never received visual feedback about the physical cube in their left hand.

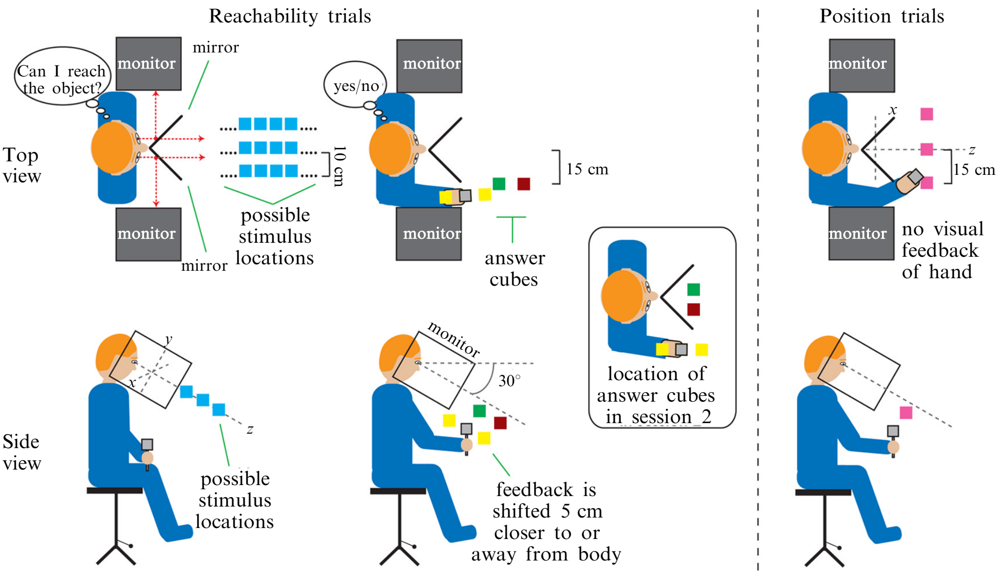


**Figure 1.** [In colour online, see http://dx.doi.org/10.1068/p6788] Top and side views of the experimental setup. The participant is sitting on a stool looking into the mirrors and sees a virtual stimulus cube in space (left column). After the stimulus is extinguished, a red and green answer cube are presented (middle column). The participant has to move the shifted visual feedback of the physical cube in his/her hand to one of the answer cubes. After every 10 reachability trials, position trials are run in which the participant has to move the physical cube in his/her hand without visual feedback to a purple test cube (right column). The inset shows a top view of the answer phase in the second session.

There were two types of trials: reachability trials and position trials. In reachability trials the stimulus, a 5 cm × 5 cm × 5 cm blue virtual cube, was presented for 1.5 s. It was presented either on the $z$-axis or 10 cm to the left or to the right of the $z$-axis. On each trial the position of the stimulus was chosen at random from six interleaved staircases. Three staircases had a starting position that was 10 cm beyond the true maximal distance that the participant could reach along the $z$-axis. The other three staircases started at a position that was 10 cm closer to the body than the participant's maximal reach distance. For one pair of staircases (one starting near and one far) targets appeared 10 cm to the left of the $z$-axis ($x = -10$ cm; $y = 0$ cm), for another pair they appeared along the $z$-axis ($x = 0$ cm; $y = 0$ cm), and for the third pair they appeared 10 cm to the right of the $z$-axis ($x = 10$ cm; $y = 0$ cm).

Once the blue cube (stimulus) disappeared, two 'answer cubes' were presented (one red, the other green). These were called answer cubes because participants used them to answer the question whether the blue stimulus cube was within reach. The answer cubes were also 5 cm × 5 cm × 5 cm. They were positioned 5 cm lower than the stimulus ($y = -5$ cm). In the first session the answer cubes were 15 cm to the right of the $z$-axis ($x = 15$ cm) and aligned in depth (see middle column, figure 1), with the closest being 18 cm nearer than the participant's maximum reach position, and the other 8 cm nearer. Either the near or the far answer cube was red (chosen at random on each trial). In the second session, the answer cubes were aligned laterally (see inset in figure 1). They were positioned 21 cm closer than the participant's maximum reach position and 7.5 cm to the left and right of the $z$-axis ($x = \pm 7.5$ cm; $y = -5$ cm).

In position trials only a 5 cm × 5 cm × 5 cm purple test cube was shown. Its position was chosen at random from three different lateral stimulus positions parallel to the $x$-axis (right column of figure 1): either 15 cm to the left of the $z$-axis ($x = -15$ cm), at the $z$-axis ($x = 0$ cm), or 15 cm to the right of the $z$-axis ($x = 15$ cm). The test cube was 5 cm below the $z$-axis ($y = -5$ cm) and 18 cm nearer than the participant's maximum reach position. Participants had to bring the physical cube(s) to those positions. They never received visual feedback about the physical cube(s) in their hand(s) during position trials.

### 2.3 *Procedure*

The first step was to determine the furthest position that the participant could reach. To do so, the participant moved his or her outstretched arm up and down holding the physical cube in his or her right hand. The position of the physical cube was tracked with the Optotrak, and the position at which the cube crossed the $z$-axis was taken as the maximum reach position. This procedure was performed in total darkness (without visual feedback from the physical cube). As the stool was positioned in such a way that the participant held his or her nose against the edges of the mirrors (figure 1), participants could hardly move their trunk forward, but they were not physically restrained.

Each participant then performed two sessions (on different days). The main differences between the sessions were the location of the answer cubes, and whether the participant held a physical cube in one or both hands (see stimulus and apparatus section). Each session consisted of two blocks of trials. In one block of trials, the visual feedback of the physical cube was shifted 5 cm in depth away from the participant's body and, in the other block, the feedback was shifted 5 cm towards his or her body. The block order within each session was counterbalanced across participants. Each block contained six staircases. Each block started with a set of reachability trials.

At the beginning of a reachability trial, participants held the physical cube(s) on their lap. In this position the visual feedback of the physical cube in their right hand was not visible owing to the limited field of view (visual feedback about the physical cube in the left hand was never provided). Then a stimulus cube was presented for 1.5 s (left column of figure 1). Participants were asked to judge whether they were able to touch the stimulus cube with the physical cube in their right hand without actually trying to do so. Immediately after the stimulus was extinguished, the red and green answer cubes were presented. If participants thought they were able to touch the stimulus cube, they moved the virtual image of the cube in their right hand (which was moved by moving the physical cube) towards the green answer cube. If they thought they were not able to touch the stimulus cube, they moved the virtual image of the physical cube towards the red answer cube (middle column of figure 1). As the virtual image of the physical cube was shifted (either 5 cm toward or away from the body), visuomotor adaptation was induced. If participants moved the virtual image of the physical cube to a location further in depth than the furthest answer cube, visual feedback of the physical cube was removed to prevent participants from seeing how the virtual image of the physical cube looks near maximum reachability. The answer cubes remained visible until an answer was given. An answer was considered to have been given if the virtual image of the physical cube was raised higher than 10 cm below the answer cubes and its velocity was lower than 1.5 cm $s^{-1}$ for 400 ms. If the stimulus cube was judged to be reachable, the location of the stimulus cube on the next trial of that staircase was shifted 2 cm away from the body. If not, the stimulus cube was shifted 2 cm closer to the body on the next trial for that staircase.

After each 10 reachability trials (one set), two position trials were performed for each of the three positions (right column of figure 1). Participants had to move the physical cube in their right hand to the virtual purple test cube without any visual feedback about the physical cube. As soon as the participant held the physical cube at the perceived location of the test cube (by the same criteria as for the answer cubes), the test cube jumped to one of the other two locations and the next trial began. In the second session, participants also performed two similar trials, each for the same three positions with the physical cube in their left hand (after the trials with the right hand). This was done to check whether the adaptation to the shifted feedback had a visual (eye orientation) or proprioceptive (arm-related) origin. If adaptation transfers to the nonexposed left hand, the origin is mainly visual.

A block of trials ended when all staircases contained 10 reversals between 'yes' and 'no' answers. Participants could take a break between the blocks. The average number of experimental trials was 301 in the first session and 333 in the second session. Each session took about 1 h.

### 2.4 *Data analysis*

2.4.1 *Reachability trials.* For each trial the *z*-coordinate of the presented stimulus position was related to the participant's maximum reach position. At each of the three lateral stimulus positions (left, middle, and right), the proportion of 'no' answers was calculated for each presented stimulus position in depth (ascending and descending staircases taken together).

Psychometric functions (cumulative normal distributions) were fitted for each participant and each feedback block using the Matlab psignifit toolbox version 2.5.6 which implements the maximum-likelihood method described by Wichmann and Hill (2001). The fitted parameters for the standard deviation (sigma) and the 50% value (considered to be the boundary of reachability) were analysed in a $2 \times 3$ repeated-measures ANOVA with the factors feedback (forward or backward shift) and lateral position (left, middle, right). Post-hoc tests were performed to determine which levels of a factor differed. Values are presented as averages with standard errors across subjects.

2.4.2 *Position trials (adaptation).* To check to what extent participants adapted to the manipulated feedback, a repeated-measures ANOVA with factors feedback, lateral stimulus position, and set number was performed on the differences between the indicated positions and the true positions of the test cubes in the position trials. Set number was included as a factor because we expect participants to gradually adapt to the shifted visual feedback. Only set numbers that contained all participants were included in the analysis (some subjects had more trials than others because it took them longer to reach the criterion of 10 reversals of the staircase). For the second session the factor hand [nonexposed (left); exposed (right)] was added to the ANOVA. Additionally, a correlation across subjects was calculated between the difference in adaptation (of the exposed hand) in the two feedback blocks and the difference between the reachability boundaries in both feedback blocks. Values are presented as averages with standard errors across subjects.

## 3 Results

### 3.1 *Session 1. Reachability trials*

Most participants overestimated their reachability in both feedback blocks (figure 2a). For the block in which the feedback was shifted away from the body, participants overestimated their reachability by 7.1 cm $\pm$ 1.2 cm. In the block in which the feedback was shifted closer to the body, reachability was overestimated by 2.3 cm $\pm$ 1.3 cm. The ANOVA on the boundaries of reachability showed a main effect of feedback ($F_{1,5} = 107.7$, $p < 0.01$) and a main effect of lateral position ($F_{2,10} = 6.5$, $p = 0.02$). Reachability judgments to the right of the $z$-axis (6.1 cm $\pm$ 1.3 cm) were overestimated more than those along the $z$-axis (4.1 cm $\pm$ 1.5 cm) and than those to the left of the $z$-axis (4.0 cm $\pm$ 1.8 cm) (see also the top half of figure 3a). As reachability was at a fixed $z$-coordinate in this study, the real boundary of reachability might be a little closer and the overestimation therefore even larger for the middle and leftmost stimuli. No interaction between feedback and lateral position was found. Figure 2b showed the data averaged over participants and lateral positions, with psychometric curves fit to the average data for illustration only. All analyses were done on fits for individual subjects (figure 2a).

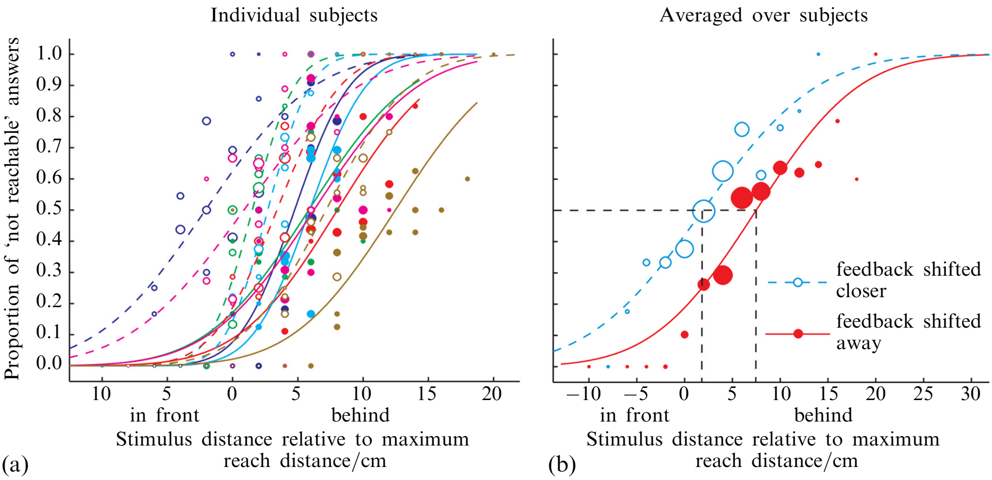


**Figure 2.** [In colour online.] Data of session 1: (a) For each participant (different colours), the proportion of 'no' answers is shown for each stimulus distance. Distances are expressed relative to the participant's maximum reach distance. Fitted psychometric curves are also shown. (b) Psychometric curves for data averaged across participants. The open blue symbols and dashed lines represent the blocks in which the feedback is shifted closer to the body, and the filled red symbols and continuous lines represent the blocks in which the feedback is shifted away from the body. The size of the symbols represents the number of trials at that stimulus distance.

The ANOVA on the sigmas (standard deviations) of the individual subjects' psychometric curves showed no effect of feedback ($F_{1,5} = 2.57$, $p = 0.17$) or lateral position ($F_{2,10} = 0.00$, $p = 0.99$), and no interaction between the factors. The average sigma was 3.72 cm.

### 3.2 *Session 1. Position trials (adaptation)*

Figure 3a shows a top view of the average indicated position of the test cubes (bottom half) and the average reachability judgments (upper half). Participants adapted to the manipulated feedback to some extent. In the block in which the feedback was shifted

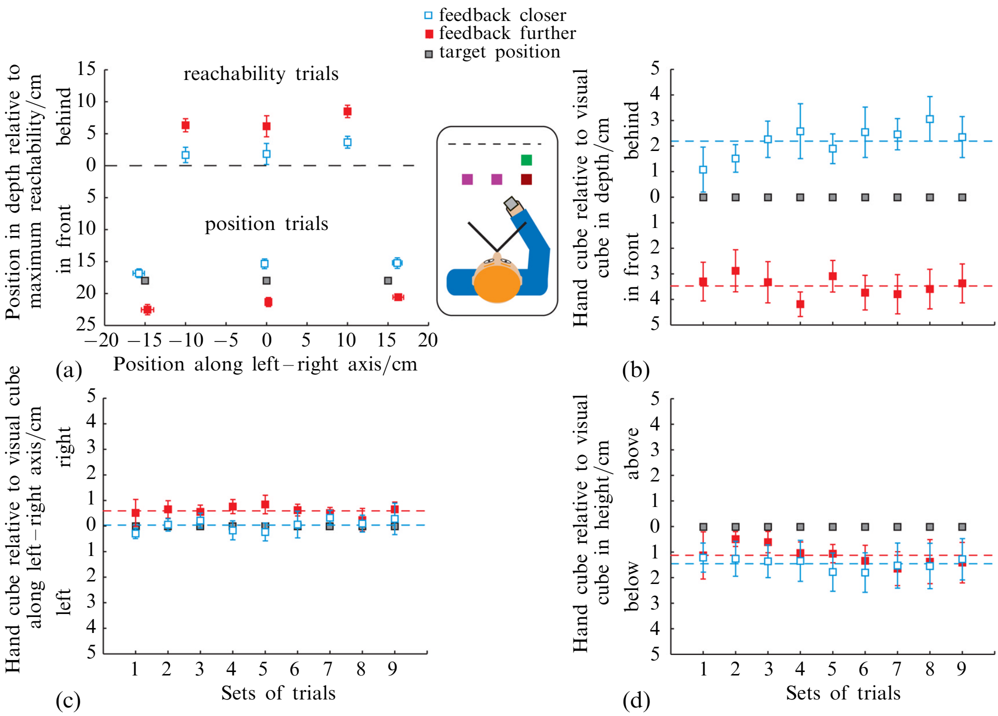


**Figure 3.** [In colour online.] Average indicated positions in session one. (a) Top view of positions of maximum reachability (top half) and positions of the test cubes in the position trials (lower half) for both feedback blocks. The dashed line shows maximum reachability. Grey squares represent the positions of the test cubes in the position trials. The inlay shows a scaled top view of the location of the test cubes and answer cubes relative to the participant. (b) Position trials: indicated position in depth after each set of 10 reachability trials. Only sets of trials containing all participants are shown. (c) Position trials: indicated lateral positions. (d) Position trials: indicated height..

5 cm away from the body, participants held the physical cube 3.5 cm $\pm$ 0.6 cm nearer than the position of the test cube. When the feedback was shifted closer to the body, participants held the physical cube 2.2 cm $\pm$ 0.6 cm further than the position of the test cube (figure 3b). Thus, participants adapted to the manipulated feedback with an average gain of 57%. The difference between the indicated positions of the test cubes in the two feedback blocks was significant ($F_{1,5} = 249.5$, $p < 0.01$). There was also a main effect of lateral stimulus position ($F_{2,10} = 8.5$, $p < 0.01$). When the stimulus was presented on the left, on average participants indicated a position that is 1.5 cm $\pm$ 0.8 cm nearer than the position of the purple test cube. This differed significantly from the average positions at the other two stimulus locations (middle: 0.2 cm $\pm$ 0.7 cm nearer than the test cube; right: 0.3 cm $\pm$ 0.8 cm further than the test cube). No effect of set number or interactions were found.

Additionally, we analysed the indicated positions in the position trials along the left – right axis (figure 3c) and in height (figure 3d). Along the left – right axis we found a significant effect of feedback ($F_{1,5} = 22.97$, $p < 0.01$): in the block in which the feedback was shifted closer to the body, participants indicated a position that was 0.04 cm to the right of the position of the test cube; whereas in the block in which the feedback was shifted further away from the body, participants indicated a position that was 0.60 cm to the right of the position of the test cube. The pattern of the average shifts was suggestive of an adaptation of joint angles in the arm, leading to a shift centred on the shoulder instead of a modified $z$-coordinate. Participants always indicated a position slightly below the test cube. No other effects were significant.

Our prediction was that the differences between the reachability thresholds in the two feedback blocks are correlated with the difference in adaptation between the blocks. No significant correlation (across subjects) was found ($r^2 = 0.08$, $p = 0.58$; see figure 4). This lack of correlation suggests that the two effects have different causes, but it could be due to the modest variability across subjects (in relation to the reliability of the magnitudes of the effects).

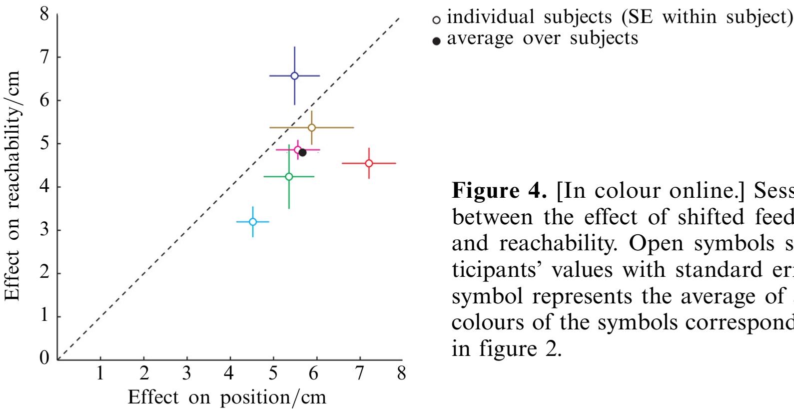


**Figure 4.** [In colour online.] Session 1. Relationship between the effect of shifted feedback on adaptation and reachability. Open symbols show individual participants' values with standard errors, and the closed symbol represents the average of all participants. The colours of the symbols correspond to the colours used in figure 2.

### 3.3 *Session 2. Reachability trials*

In the second session the location of the answer cubes differed with respect to session 1. Additionally, participants performed the position trials with the nonexposed, as well as with the exposed, hand. In the second session, participants again overestimated their reachability in both feedback blocks (figures 5 and 6; top half). On average, participants overestimated their reachability by 7.6 cm $\pm$ 2.3 cm. This was significantly further than the estimates in the first session ($t = 3.20$, $p < 0.01$), meaning that in the second session participants thought they could reach objects that were further away. The ANOVAs on the sigmas and thresholds derived from the psychometric curves of the second session revealed no main effects or interactions. The average sigma is 6.25 cm, which was significantly larger than the sigma in the first session ($t = 3.76$, $p < 0.01$). Thus participants were less precise in their reachability judgments in the second session.

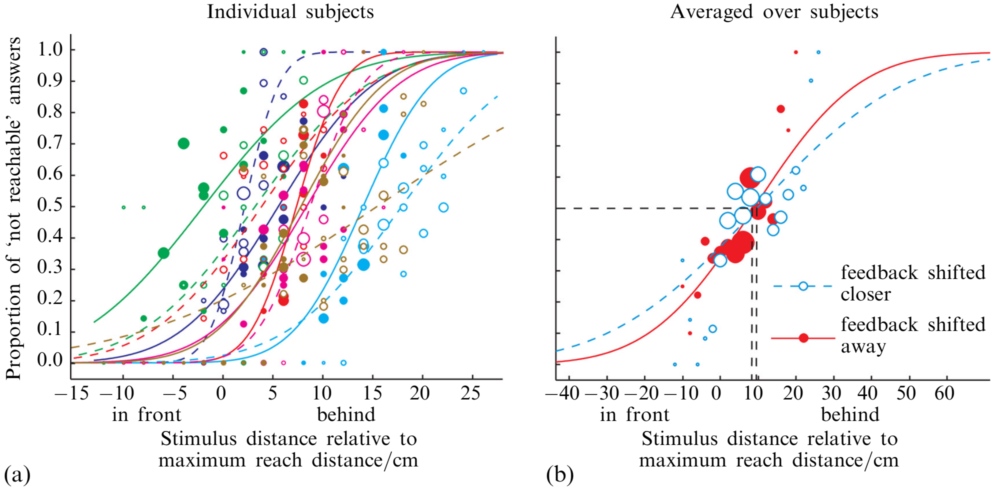


**Figure 5.** [In colour online.] Reachability data of the second session in the same format as figure 2.

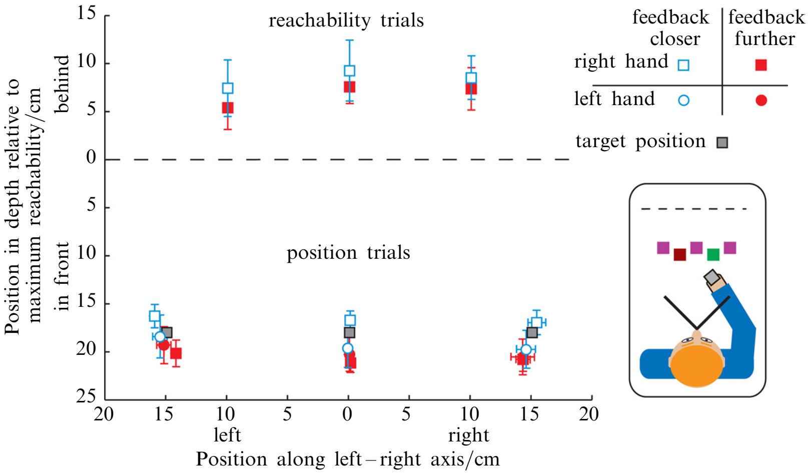


**Figure 6.** [In colour online.] Average indicated positions in session two (same format as figure 3a), with circular symbols indicating positions with the left hand.

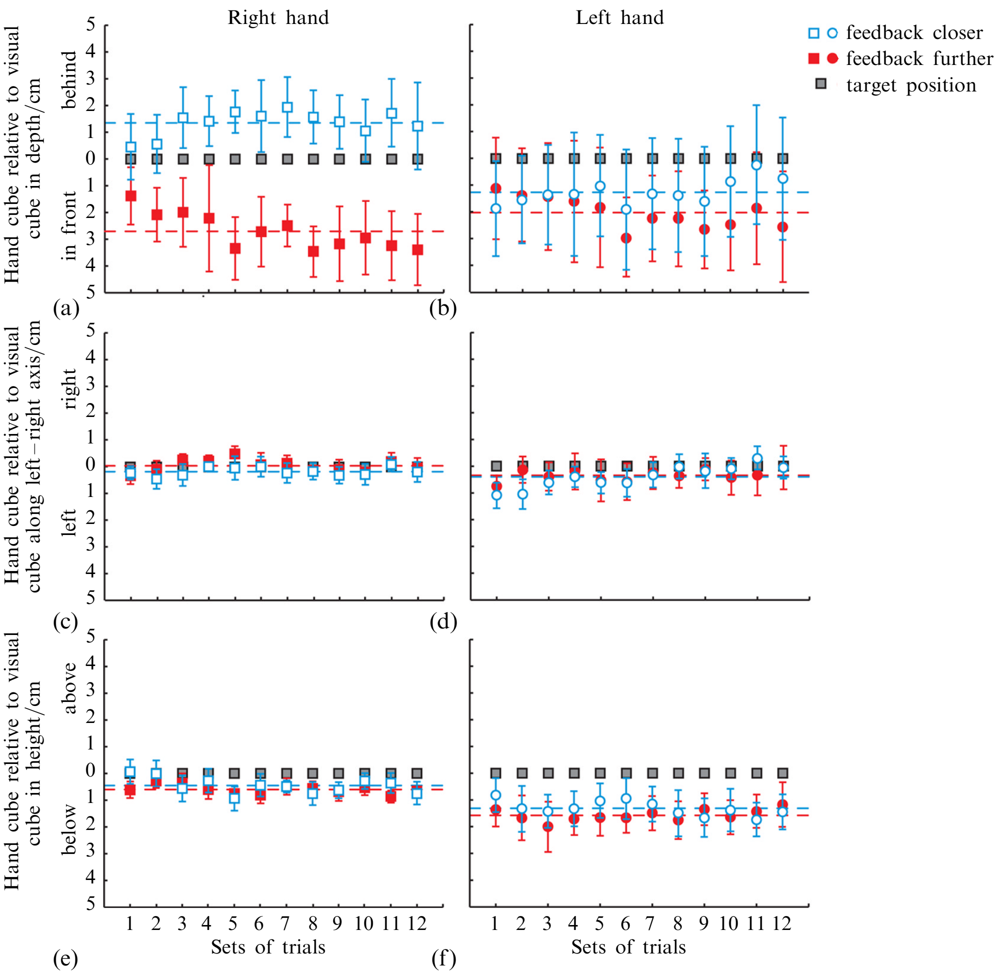


**Figure 7.** [In colour online.] Average indicated positions in position trials in session two. (a) – (b) Indicated positions in depth, (c) – (d) indicated lateral positions, and (e) – (f) indicated height. The two columns show the positions for the two hands. The format is the same as in figures 3b – 3d.

### 3.4 *Session 2. Position trials (adaptation)*

Participants did adapt to the manipulated feedback with their exposed hand, but as in the first session, not to the full extent (figure 7a). In the block in which the feedback was shifted 5 cm away from the body, participants held the physical cube 2.7 cm ± 1.1 cm closer than the position of the test cube (figure 6). When the feedback was shifted closer to the body, participants held the physical cube 1.3 cm ± 1.0 cm further than the position of the test cube. Their exposed hand adapted by about 41% of the distorted feedback. This amount of adaptation did not differ significantly from the adaptation of the exposed hand in the first session (57%). The nonexposed hand also adapted, but much less than the exposed hand (figures 6 and 7b). In the block in which the feedback was shifted 5 cm away from the body, participants held the physical cube 2.0 cm ± 1.8 cm closer than the position of the test cube (figure 6). When the feedback was shifted closer to the body, participants held the physical cube 1.3 cm ± 1.9 cm closer than the position of the test cube. Participants adapted with their left hand by about 8% of the distorted feedback, which means that about 19% of the adaptation of the exposed hand transferred to the nonexposed hand. For the exposed hand, we can consider this amount to represent the visual component of the adaptation.

The ANOVA showed a clear difference between the indicated positions of the test cubes in both feedback blocks ($F_{1,5} = 12.02$, $p = 0.01$). The interaction between feedback and hand was also significant ($F_{1,5} = 30.53$, $p < 0.01$); the exposed hand adapted significantly more than the nonexposed hand. No main effects of lateral stimulus position, set number, or hand were found. An interaction was found between feedback and set number ($F_{11,55} = 2.00$, $p = 0.04$). The difference between the physical cube and the test cube increased with set number, which suggests that participants gradually adapted to the distortion. We can estimate visually from figure 7a that adaptation was complete after 3 blocks (30 trials), in line with the results in figure 3b and earlier results (Smeets et al 2006). We found no significant effects or interactions for indicated positions along the left–right axis or in height (figures 7c–7f).

No significant correlation across subjects was found between the effect on position (amount of adaptation for the exposed hand) and the effect on reachability (figure 8a—$r^2 = 0.05$, $p = 0.67$). Thus, a participant that adapted more to the shifted feedback did

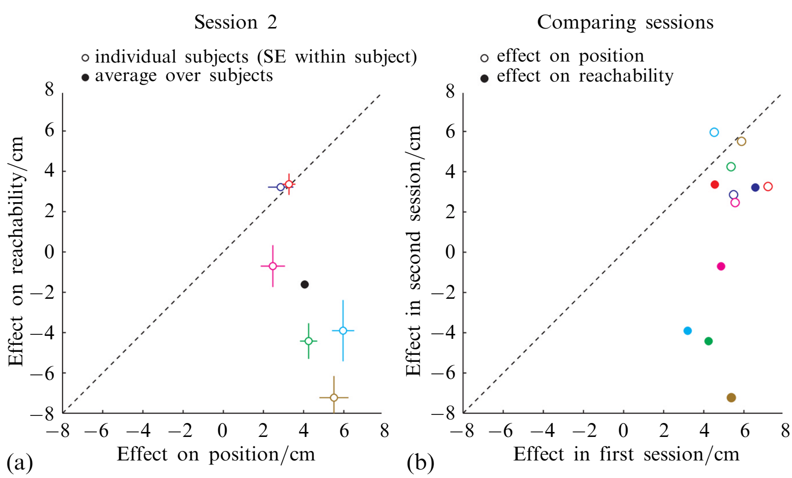


**Figure 8.** [In colour online.] Effect of feedback in session two and compared between the two sessions. (a) Relationship between the effect of shifted feedback on position and reachability in session two. The format is the same as figure 4. (b) The effect on reachability and on position in the second session plotted against the effect on reachability and on position in the first session. The colours of the symbols correspond to the colours used in figure 2.

not necessarily have a larger shift in reachability (figure 8a). In figure 8b the individual shifts in reachability and amounts of adaptation were compared across the first and second session. No correlation was found between the amount of adaptation in the first and second session or between the shift in reachability in the two sessions.

## 4 Discussion

In this study we wanted to investigate whether shifted visual feedback about the hand affects reachability judgments and, if so, what causes the shift in reachability. We found that reachability judgments can be changed by shifted visual feedback, but this change is not correlated with the amount of visuomotor adaptation. Moreover, we only found consistent changes in reachability judgments in the first session, in which participants indicated their answers by performing movements in depth away from their body.

In the second session reachability judgments were not systematically affected by the shifted feedback, although the movements for which feedback was provided were made only 20 cm closer than the maximum reachable distance. In this session participants were also less precise in their answers on reachability trials than in the first session (larger sigmas of the psychometric curves), even though the task was exactly the same, which suggests that moving the (visible) arm near the border of reachability helps judge reachability. The amount of adaptation that we found, and the amount of transfer between the hands, is similar to that found by van den Dobbelsteen et al (2003).

On the basis of our results, we can reject any mechanism that explains changes in reachability judgments by changes in estimates of limb or target position (such as the proposals that only the position of the hand is misjudged or that vision is calibrated by touch, from the introduction). The lack of a clear correspondence between the effects on the two tasks is not because the judgments are too variable to reveal any effects: all subjects showed significant adaptation in all sessions and they all showed a significant effect on judged reachability, except for one subject in the second session (refuting the proposal that only joint angles are misjudged). Thus the lack of correlation is not simply the consequence of masking a high correlation by variability in the independent measures. All subjects showed a similar amount of adaptation, which was similar for the two sessions (open symbols in figure 8b). In contrast, the effect of the shifted feedback on reachability differed considerably between subjects in the second session (filled symbols in figure 8b). What can have caused this difference between the sessions in the consistency of the effect on reachability?

A possible explanation for the lack of consistency might be that different subjects adapted to the same extent, but by using different mechanisms. The left arm showed 19% of the effect found for the right arm, so the visual contribution to adaptation is limited but not totally absent. Some subjects could mainly adapt to a displacement of visual feedback away from their body by assuming that their arm is extended further than it actually is (a change in felt joint angles). This would mean that there would be little room for further extension, so that the perceived maximal reachable distance is reduced. Other subjects might have mainly adapted to the same shift in visual feedback by assuming that their upper and lower arm are longer than they actually are (without a change in proprioception of the joint angles). These subjects will think that they can reach further with a fully extended arm than they actually can. Although we can come up with possible mechanisms and combinations of mechanisms to explain the various behaviours that we observed, we have no idea what determines which subject uses which mechanisms, so this would be no more than a reformulation of the results.

Not being able to find a consistent change in reachability judgments is not specific to the experimental paradigm that we used in the present study. In a previous study with a different paradigm, no changes in reachability judgments were found (de Grave et al 2011). In that study we tried to replicate earlier effects of tool use on reachability judgments (Witt et al 2005), but failed to do so. The present study shows that the mixed effects on reachability are not limited to tool use, but are also found in visuomotor adaptation. This is unfortunate, because it makes them very difficult to interpret. What we can confidently conclude is that judgments of reachability are largely independent of visuomotor adaptation.

**References**

Ackroyd K, Riddoch M J, Humphreys G W, Nightingale S, Townsend S, 2002 "Widening the sphere of influence: using a tool to extend extrapersonal visual space in a patient with severe neglect" *Neurocase* **8** 1 – 12

Berti A, Frassinetti F, 2000 "When far becomes near: remapping of space by tool use" *Journal of Cognitive Neuroscience* **12** 415 – 420

Bootsma R J, Bakker F C, van Snippenberg F J, Tdlohreg C W, 1992 "The effects of anxiety on perceiving the reachability of passing objects" *Ecological Psychology* **4** 1 – 16

Botvinick M, Cohen J, 1998 "Rubber hands 'feel' touch that eyes see" *Nature* **391** 756

Carello C, Grosofsky A, Reichel F D, Solomon H Y, Turvey M T, 1989 "Visually perceiving what is reachable" *Ecological Psychology* **1** 27 – 54

Coello Y, 2005 "Spatial context and visual perception for action" *Psicologia* **26** 39 – 59

Coello Y, Iwanow O, 2006 "Effect of structuring the workspace on cognitive and sensorimotor distance estimation: no dissociation between perception and action" *Perception & Psychophysics* **68** 278 – 289

Coello Y, Magne P, 2000 "Determination of target distance in a structured environment: selection of visual information for action" *European Journal of Cognitive Psychology* **12** 489 – 519

Collins T, Schicke T, Röder B, 2008 "Action goal selection and motor planning can be dissociated by tool use" *Cognition* **109** 363 – 371

Dobbelsteen J J van den, Brenner E, Smeets J B J, 2003 "Adaptation of movement endpoints to perturbations of visual feedback" *Experimental Brain Research* **148** 471 – 481

Farnè A, Bonifazi S, Làdavas E, 2005a "The role played by tool-use and tool-length on the plastic elongation of peri-hand space: a single case study" *Cognitive Neuropsychology* **22** 408 – 418

Farnè A, Iriki A, Làdavas E, 2005b "Shaping multisensory action-space with tools: evidence from patients with cross-modal extinction" *Neuropsychologia* **43** 238 – 248

Foley J M, 1968 "Depth, size and distance in stereoscopic vision" *Perception & Psychophysics* **3** 265 – 274

Gamberini L, Seraglia B, Priftis K, 2008 "Processing of peripersonal and extrapersonal space using tools: evidence from visual line bisection in real and virtual environments" *Neuropsychologia* **46** 1298 – 1304

Grave D D J de, Brenner E, Smeets J B J, 2011 "Using a stick does not necessarily alter judged distances or reachability" *PLoS ONE* **6** e16697

Heft H, 1993 "A methodological note on overestimates of reaching distance: distinguishing between perceptual and analytical judgments" *Ecological Psychology* **5** 255 – 271

Higuchi T, Imanaka K, Patla A E, 2006 "Action-oriented representation of peripersonal and extrapersonal space: insights from manual and locomotor actions" *Japanese Psychological Research* **48** 126 – 140

Holmes N P, Calvert G A, Spence C, 2004 "Extending or projecting peripersonal space with tools? Multisensory interactions highlight only the distal and proximal ends of tools" *Neuroscience Letters* **372** 62 – 67

Holmes N P, Sanabria D, Calvert G A, Spence C, 2007 "Tool-use: capturing multisensory spatial attention or extending multisensory peripersonal space?" *Cortex* **43** 469 – 489

Holmes N P, Spence C, 2004 "The body schema and multisensory representation(s) of peripersonal space" *Cognitive Processes* **5** 94 – 105

Longo M R, Lourenco S F, 2006 "On the nature of near space: effects of tool use and the transition to far space" *Neuropsychologia* **44** 977 – 981

Maravita A, Husain M, Clarke K, Driver J, 2001 "Reaching with a tool extends visual – tactile interactions into far space: evidence from cross-modal extinction" *Neuropsychologia* **39** 580 – 585

Mark L S, Nemeth K, Gardner D, Dainoff M J, Paasche J, Duffy M, Grandt K, 1997 "Postural dynamics and the preferred critical boundary for visually guided reaching" *Journal of Experimental Psychology: Human Perception and Performance* **23** 1365 – 1379

Norman J F, Todd J T, Perotti V J, Tittle J S, 1996 "The visual perception of three-dimensional length" *Journal of Experimental Psychology: Human Perception and Performance* **22** 173 – 186

Pegna A J, Petit L, Caldara-Schnetzer A S, Khateb A, Annoni J M, Sztajzel R, Landis T, 2001 "So near yet so far: neglect in far or near space depends on tool use" *Annals of Neurology* **50** 820 – 822

Rochat P, Wraga M, 1997 "An account of the systematic error in judging what is reachable" *Journal of Experimental Psychology: Human Perception and Performance* **23** 199 – 212

Smeets J B J, Dobbelsteen J J van den, Grave D D J de, Beers R J van, Brenner E, 2006 "Sensory integration does not lead to sensory calibration" *Proceedings of the National Academy of Sciences of the USA* **103** 18781 – 18786

Wichmann F A, Hill N J, 2001 "The psychometric function: I. Fitting, sampling, and goodness of fit" *Perception & Psychophysics* **63** 1293 – 1313

Witt J K, Proffitt D R, Epstein W, 2005 "Tool use affects perceived distance, but only when you intend to use it" *Journal of Experimental Psychology: Human Perception and Performance* **31** 880 – 888

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