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Shifted visual feedback of the hand affects reachability judgments in interception

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ABSTRACT

Estimating whether an object is reachable is important if one intends to interact with the object. If an object is moving, it will be reachable only within a certain time-window. In such situations, motion of the object relative to the body has to be taken into account to judge the moment at which the target becomes reachable. We know that judgments of reachability are influenced by displaced visual feedback about the position of the hand when objects are static. Here we examine whether displaced feedback of the hand also influences reachability judgments when reachability is temporally constrained because the object is moving. The task for the subjects was to intercept a virtual cube with their unseen index finger as soon as the cube was considered to be reachable. Subjects received visual feedback about the position of their index finger, but this feedback was shifted in depth by 5 cm, either away from or closer to their body. The region that was judged to be reachable was larger when feedback of the hand was shifted away from the body than when the feedback was shifted closer to the body. This effect was correlated with the spatial error committed at the interception point. We conclude that all judgments about the surrounding space are adjusted in relation to the shifted visual feedback of the hand.

1. Introduction

One of the most common motor tasks in daily life is to reach out to manipulate an object. In order to decide whether it is worthwile starting to do so, the visuomotor system requires a judgment about whether the object is reachable, based on variables like body posture and the length of the arm. Studies of reachability examine the range of positions that one judges to be reachable. In spite of the apparent simplicity with which one estimates the reachability of an object, numerous studies have demonstrated that doing so is not trivial. Indeed, previous literature has reported that visual judgments of reachability can be influenced by various factors. Carello et al. (1989) proposed that misjudging the stability of one's posture while reaching out to an object is one of the factors that cause people to think that they can reach a static object that they cannot (Bootsma et al., 1992; Gabbard, Ammar, & Lee, 2006; Heft, 1993; Mark et al., 1997). This explanation is known as the postural stability account. As the risk of falling over is lower in a seated position, participants are more confident of reaching out further when seated, leading to overestimations of reachability (Robinovitch, 1998). Another explanation for overestimating reachability is the "whole body engagement" hypothesis (Rochat & Wraga, 1997). This states that participants are not able to account for the constraints of the experimental set-up when performing the task (e.g. participants fail to consider the restriction of their range of motion when the trunk is strapped to the chair). Yet another explanation is that the circumstances could affect our visual judgments of distance (Sousa, Brenner, & Smeets, 2010). Coello (2005) showed that reachability judgments are overestimated in impoverished visual conditions (Coello & Iwanow, 2006). Witt, Proffitt, and Epstein (2005) showed that objects that are beyond reach without a tool look closer and reachable when holding a tool. According to Berti and Frassinetti (2000), the tool was assimilated to the hand like an artificial extension of the body, causing one to believe that one could reach further. Subsequent studies demonstrated specific kinematic changes because of tool-use that suggested an update of the somatosensory representation congruent with an increased length of the arm (Cardinali et al., 2009). They also demonstrated that this gradual elongation from the hand towards the tip of the tool needed an active physical connection between them (Longo & Lourenco, 2006; Gamberini et al., 2008). In fact, the re-size of the near space seems to require a clear intention to use the tool

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(active use), since the mere presence of a long stick resting near the hand (Maravita et al., 2001) or passively held (Farnè, Bonifazi, & Làdavas, 2005; Witt, Proffitt, & Epstein, 2005) produced no such effect. Nevertheless, the use of a tool is not strictly necessary. The extension of reachable space can also be modified by displacing the felt from the seen position of the hand (Holmes & Spence, 2004). de Grave, Brenner, and Smeets (2011b) recently reported that such modifications are not correlated with the amount of visuomotor adaptation, although some other studies supported the idea that reachability judgments are closely linked to changes in visuomotor variability (Bourgeois & Coello, 2012).

A common aspect of all these studies is that subjects performed a perceptual judgment about the reachability of either a static (Denise et al., 2011) or a moving object (Fischer et al., 2003; Delevoye-Turrell, Vienne, & Coello, 2011; de Grave, Brenner, and Smeets (2011a)), each demanding different information. However, as reachability judgments are thought to form the basis of decisions to make a movement, we sought to examine whether the influence of displaced visual feedback on estimating reachability is also evident when making such decisions about moving objects. Specifically, we investigated whether displacing the feedback affected the actions towards moving objects, imposing a time constraint to the reachability judgment. We chose an interceptive hand movement towards a moving object, since the temporal cues needed to hit the target cannot be recruited merely from the visual information of the target motion (Brouwer, Brenner, & Smeets, 2003), demanding an estimation of the reachability. This required estimation in order to judge when to start the movement is based on two evidences: first, if reachability judgments were uniquely sustained on visual cues, feedback displacement would have no effect on them. Second, the resolution of the on-line control when making temporal adjustments is lower comparing to spatial ones (Brenner & Smeets, 1997; Brenner, Smeets, & de Lussanet, 1998). Thus, when one reaches out to interact with a moving object one must estimate when the object will be reachable. Consequently, motion of the object relative to the body has to be taken into account, and a continuous update of the reachability judgment has to be made. The complexity of this task consists of taking into account the velocity of the object and the velocity and duration of the planned arm movement. In this context, our experimental design allowed us to test whether visual information presented a strong dominance when localizing the hand in the interceptive task, or whether proprioceptive information assists the vision of our hand crucially when the location coding implied body parts involved in the action (Rodriguez-Herreros & Lopez-Moliner, 2011; Rossetti, Desmurget, & Prablanc, 1995).

2. Methods

2.1. Subjects

Six right-handed volunteers (4 women; mean age 31.5 ± 11.4 years) participated in the experiments, including two of the authors. Except for them, all subjects were naive with respect to the experimental hypothesis. Participants had normal or corrected-to-normal visual acuity and no one had any history of neuromuscular disorders. Prior to their inclusion in the study, participants gave their informed consent. The local ethics committee approved this study.

2.2. Apparatus

We used the same set-up as (de Grave, Brenner, & Smeets, 2011a, see Fig. 1) to present virtual stimuli. In a dark room, subjects sat on a height-adjustable stool in front of two mirrors in which each eye saw a seperate CRT monitors (1096×686 pixels, 47.3×30.0 cm, 160 Hz). A three-dimensional virtual environment was created by presenting different images to the left and the right eye using this combination of mirrors and monitors. 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. Infrared markers were attached to the index finger tip of the subjects' dominant right arm to register hand movements. These movements were recorded at 250 Hz with a 0.01 mm spatial resolution using the Optotrak 3020 motion analysis system (Northern Digital, Inc.). The individual position data time series were processed with a low-pass Butterworth filter (cutoff frequency of 6 Hz) for further analysis. Velocity and acceleration data were derived from the smoothed position data.

2.3. Stimuli

At the start of each trial, a start position for the finger was presented (a $1 \times 1 \times 1$ cm pink cube located 15 cm to the right of the *z*-axis ($x = 15$)) (see Fig. 1). A yellow cube (also $1 \times 1 \times 1$ cm) provided visual feedback about the position of the index finger. Stimuli consisted of a $5 \times 5 \times 5$ cm blue target cube that moved along one of several paths at a constant speed of 15 cm/s for a fixed duration of 1.5 s. On each trial the trajectory of the target was chosen at random from twelve interleaved staircases. For six staircases, the starting position of the target was such that the target passed the subject's body 10 cm closer than the maximal distance that the participant could reach along the *z*-axis. For the other six staircases the starting position of the target was 10 cm further than the participant's maximal reach distance. The six pairs of staircases (one starting near and one far) differed with respect to motion direction of the target (from left to right or from right to left) and trajectory of the target (approaching, departing or frontal). On one third of the trials the target moved parallel to the lateral axis (x) (frontal trials). The other two thirds of trials were trajectories with an angle of 20° with respect to the x axis: one third for departing trials (moving away for the body), and the other for approaching (moving closer to the body).

2.4. Procedure

The first step was to determine the furthest position that the participant could reach (true reachability). To do so, the participant moved his or her outstretched right arm from left to right, crossing the sagittal plane. The position of the marker on his/her finger was tracked with the Optotrak. This procedure was performed in total darkness (without visual feedback about the position of the index finger). The finger's path was used to determine the starting positions of the target's trajectories, in a way that the target's initial positions of the first trial of each staircase were determined by the minimum and maximum Z coordinates of the finger's path. For instance, initial position of trial 1 in staircase 1 (departing target from left to right) was the X min and Z min coordinates. As the stool was positioned in such a way that the participant held his or her nose against the edges of the mirrors (Fig. 1), participants could hardly move their trunk forward, but they were not physically restrained in any other way.

Each participant performed two blocks of trials, with a break between them. The blocks differed with respect to the visual feedback about the position of the hand. In one block of trials the visual feedback 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 authors knew about the manipulation of the visual feedback, although they could not distinguish the specific displacement (away, closer) of each block. The four naïve participants were not informed about the feedback manipulation and none of them reported any difference between the seen and the felt position of their finger. Each block contained 12 staircases. At the

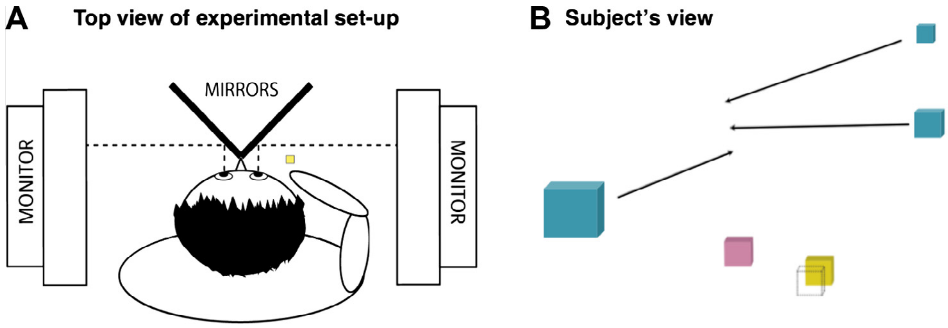

Fig. 1. Top view (A) and participant's view (B) of the experimental setup (not to scale). The blue cubes indicate the moving targets that participants had to reach (only one cube appeared in each trial). The yellow cube represents the visual feedback about the position of the index finger. Indicated is the situation in which the visual feedback was 5 cm further away than the real finger position (dotted cube). The pink cube represents the starting position. The yellow cube had to be moved to the pink one in order to start the trial. The task was then to intercept the blue cube, if doing so was deemed possible. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

start of each block participants performed 20 practice trials to get familiar with the task. The two feedback shifts were separated in two different blocks in order to avoid the participants to be aware of the distortion. After the experimental sessions, participants were asked about the feedback displacement and none of them reported awareness of the distortion.

The starting position (pink cube) was presented at the beginning of each trial. Participants had to move the virtual image of the index finger (yellow cube) to the start position in order to start the trial. The index finger was considered to be at the start position when the virtual image of the index finger was raised higher than 10 cm below the start position and its velocity was lower than 1.5 cm/s for 400 ms. As soon as the index finger was at the starting position, the moving target cube was presented for 1.5 s. The task was to intercept the cube with the index finger as soon as it was judged to be reachable. If the target was judged to be unreachable along its entire path, the subject had to remain at the starting position and wait for the next trial. If the target was judged to be reachable, the stimulus on the next trial of that staircase was shifted 2 cm away from the body. If the target was judged to be unreachable (i.e. the subject did not move), the stimulus was shifted 2 cm closer to the body on the next trial for that staircase. On trials that were judged to be reachable, subjects had to bring their hand back to the starting position in order to start the next trial. Visual feedback about the position of the hand was provided throughout a block, except when the index finger tip was within 10 cm of the target. The order of the blocks was counterbalanced across participants. A block of trials ended when all staircases contained 10 switches between trials in which subjects moved the hand and trials in which they did not. The average number of trials was 651 and each block took about one hour.

2.5. Analysis

In all analysis, the knowledge of the experimental manipulation was not considered as a factor, since preliminary analyses had revealed a lack of statistical main effects and interactions ($p > .6$ for all comparisons). We know the z (depth) and x (lateral) coordinates of the entire target path for each trial. The minimal distance between the target trajectory and the starting position of the hand (real position of the finger marker) was used to determine the participant's performance on judging the reachability of the object. The proportion of "unreachable" answers (trials in which participants did not move their finger because they judged the target as not reachable throughout the path) was the subjects' response that we calculated for each distance to the path. This was done for every direction of the stimulus (departing, approaching, frontal), combining data from the ascending and descending staircases. Psychometric functions (cumulative normal distributions) were fitted for each participant and each block using the R statistic software, which implements the maximum-likelihood method described by Wichmann and Hill (2001). We performed a 2×3 repeated measures ANOVA to evaluate the fitted parameters for the standard deviation (sigma) and the judged reachability threshold with the within-subject factors feedback (forward or backward shift), and direction of the stimulus (departing, approaching, frontal). Post-hoc tests were conducted to see which levels of a factor differed. Additionally, a subsequent analysis was performed to determine whether approaching and departing objects were judged reachable and intercepted at different distances. We measured the target position in trials in which participants moved the hand towards the target. Specifically, we compared the location of the target at the onset and at the offset of the hand movement for both approaching and departing paths. We conducted a $2 \times 2 \times 2$ repeated measures analysis of variance (ANOVA) with factors feedback (forward or backward shift), direction of the stimulus (departing, approaching) and time (onset, offset).

Finally, hand movement trajectories were determined from the three-dimensional spatial coordinates of the position of the index finger. The beginning and end of each hand movement were defined as the moments the hand reached a velocity that was higher and lower than 1.5 cm/s respectively. Spatial errors in depth were defined as the difference between the z position of the hand and the z position of the target at the moment the hand movement ended (positive errors indicate that the hand was further than the target). The individual systematic error for a given condition was the mean of the spatial errors defined in this manner. The euclidian distance between the starting and endpoint position of the finger was also calculated for every hand movement. To check the magnitude of the adaptation to the feedback displacement, a repeated measures ANOVA with factors feedback and direction of the object's path was performed on the individual systematic errors and on the movement distances. For all the analysis, trials in which the reaction time (time interval from the target onset until the movement onset) was shorter than 700 ms (most of them departing) were removed from the sample, since the position at which the target was intercepted is likely to have been limited by the reaction time rather than by judgments of when the target came within reach. Threshold for statistical significance was set at $p < .05$. Post-hoc comparisons were performed using paired sample t-tests.

3. Results

3.1. Reachability judgments

Each panel of Fig. 2 represents the psychometric curves of all subjects. Panel A shows that the reachability judgments followed the shift of the hand's visual feedback: the grey curves (feedback shifted closer) are positioned at smaller distances than the black curves (feedback shifted away). Panel B shows no clear effect of the direction of the stimulus.

The ANOVA on the reachability thresholds (50% values of psychometric curves) showed a main effect of visual feedback displacement (away = 68.4 cm, closer = 55.6 cm, $F_{(1,5)} = 46.4$, $p < .01$). On average, participant's reachability boundary was about 13 cm further away when the feedback was shifted 5 cm away from the body compared to when the feedback was shifted 5 cm closer to the body. This value is slightly more than the sum of the two feedback shifts (10 cm). No significant effect of stimulus direction was found ($F_{(2,10)} = 2.27$, $p = .15$), and the interaction was also not significant ($F_{(2,10)} = 1.45$, $p = .28$). The analysis of the variability (the standard deviation of the fitted function, corresponding to the slopes of the psychometric curves) yielded no significant effects of feedback conditions ($F_{(1,5)} = 3.8$, $p = .11$), stimulus direction ($F_{(2,10)} = 1.84$, $p = .21$) or interaction between these factors ($F_{(2,10)} = 0.82$, $p = .47$). On average, the standard deviation was 13.8 cm.

To test whether participants estimate the reachable position of the object taking into consideration the time employed to intercept the target at this position, we measured where the target was when participants decided to move and when they ended the movement. Fig. 3 depicts a top view of the target locations of a representative subject for both closer (3A–3B) and away (3C–3D) feedback displacements. Target locations at the onset of the movement corresponded to A and C panels, whereas B and D were for target positions at the end of the hand movement. The pattern of data for the rest of the subjects is very similar (not shown). The black rectangle in the lower part of both panels indicates where the visual feedback of the index finger was required to be in order to start the trial. The real position of the index finger at that time (purple dots) was not centered on the black rectangle because of the shift in the feedback. Thus the starting position of the finger differed between the feedback conditions.

We observed a significant main effect of the feedback distortion both at the beginning (away = −41.42 cm, closer = −34.76 cm, $F_{(1,5)} = 12.47$, $p = .016$) and at the end of the movement (away = −41.45 cm, closer = −34.6 cm, $F_{(1,5)} = 13.05$, $p = .015$), showing that the target was judged reachable further when the displacement of the feedback was away from the body, in both cases. In contrast, for the direction of the movement, we found significant differences only at the onset (approaching = −43.4 cm, departing = −36.1 cm, $F_{(1,5)} = 19.1$, $p = .007$), whereas the location of departing and approaching objects did not differ when the hand movement ended (approaching = −38.5 cm, departing = −37.5 cm, $F_{(1,5)} = 1.2$, $p = .32$). Neither of the interactions was found to be significant.

3.2. Hand movements

Fig. 4 shows that the spatial error in depth (difference between z-coordinates of the target and the real hand) at the end of the movement varied considerably between subjects and visual feedback conditions.

We found a significant effect of feedback condition (away: −13.99 cm, closer: −2.6 cm, $F_{(1,5)} = 54.2$, $p < .001$) but not of the direction of the stimulus ($F_{(2,10)} = 3.15$, $p = .09$), and the interaction was not significant ($F_{(2,10)} = 0.66$, $p = .53$). Neither the movement

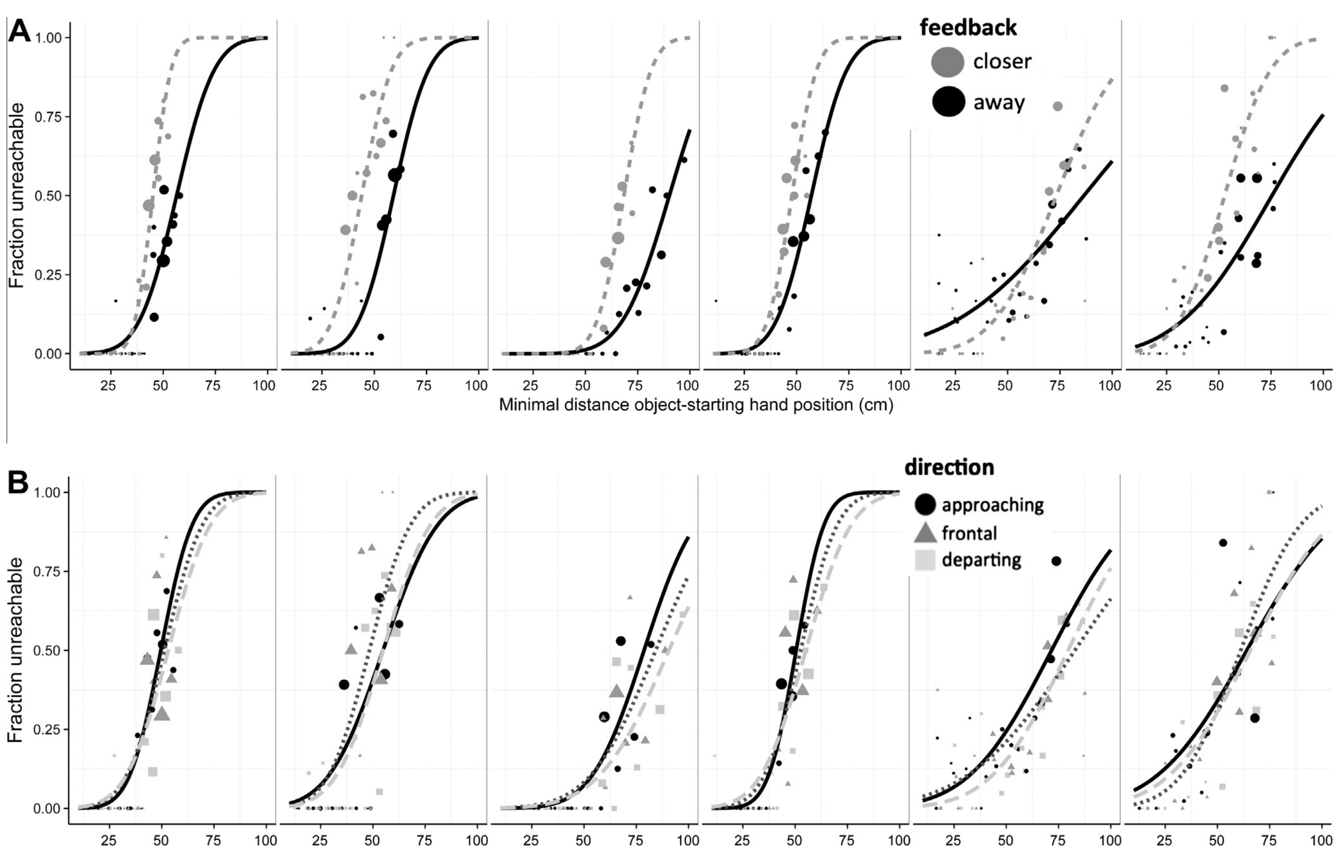

Fig. 2. (A) Psychometric curves for each subject for the two feedback conditions. Black (continuous line) represents trials in which feedback was shifted away from the body and grey (dashed line) ones in which feedback was shifted closer to the body. (B) Psychometric curves for each subject for the three directions of target motion. Solid black line (disks) represents approaching targets, dashed light grey line (squares) represents departing targets, and dotted dark grey line (triangles) represents frontal trials. Size of the dots represent the number of trials: big dots (>20 trials), medium dots (5–20 trials) and small dots (<5 trials).

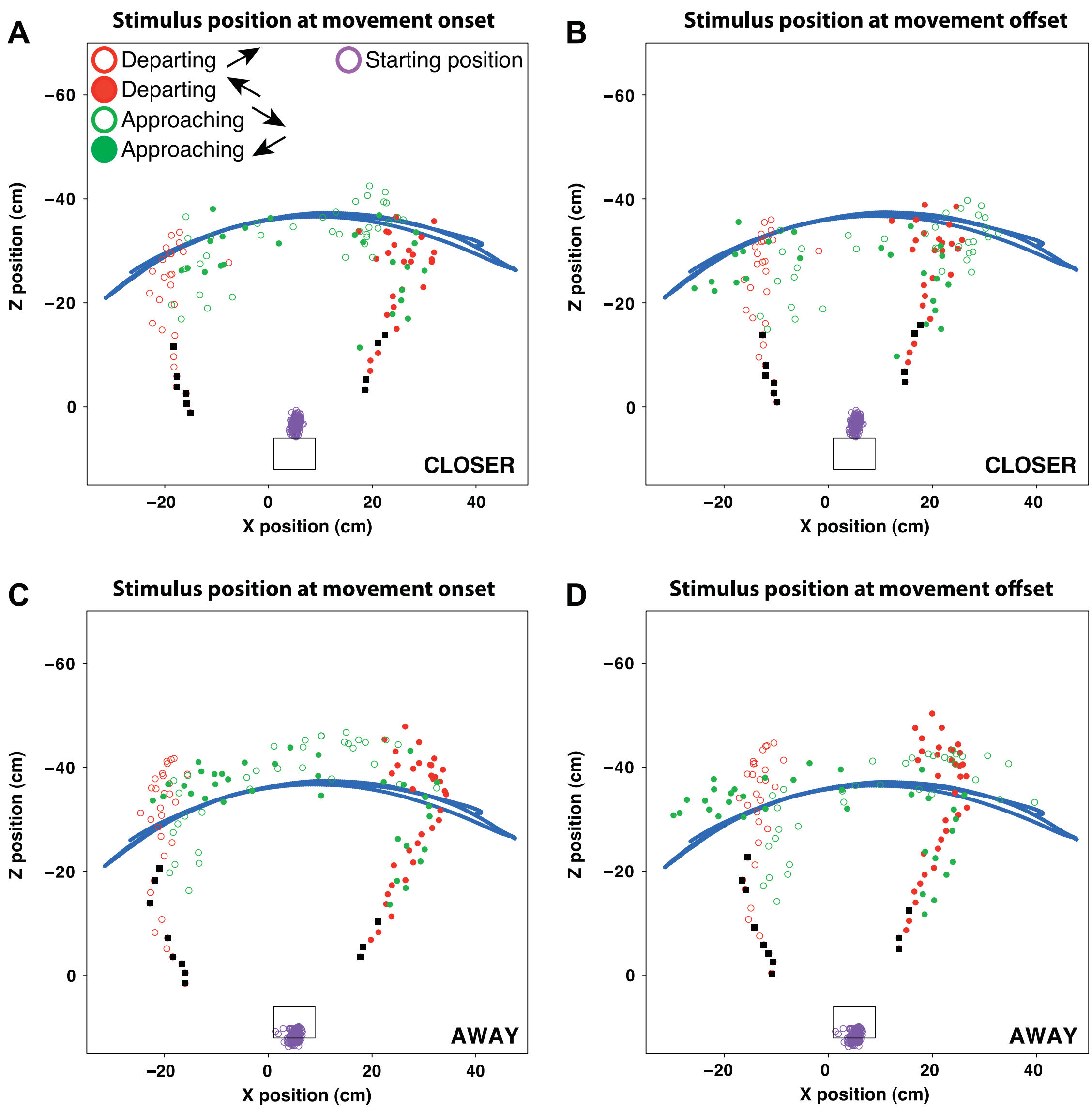

Fig. 3. Top view of the target locations at the onset (A–C) and at the offset (B–D) of the hand movement for a representative subject. A and B panels corresponded to the feedback distortion 5 cm closer than the real finger position and C–D for 5 cm away. The reaching range of the arm is represented by the blue line. Purple dots are the starting positions of the finger. Other symbols indicate the target position. Colors indicate the direction of the target's path (see Legend). Trials in which the reaction time was shorter than 700 ms are shown as black squares (removed from the analysis). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

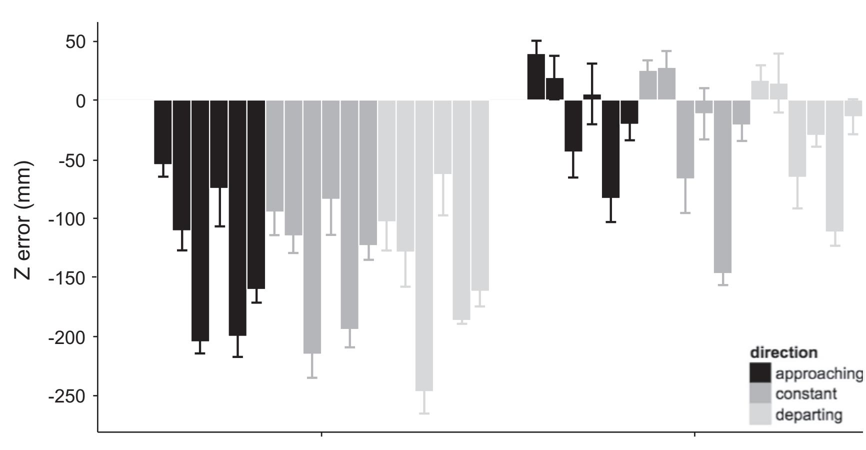

Fig. 4. The average systematic error at the end of the movement of each subject for both feedback conditions (away, closer) and the three directions of motion: approaching (black), frontal (dark grey) and departing (light grey). Error bars show the SEM.

direction ($F_{(2,10)} = 0.12$, $p = .88$) nor the feedback condition ($F_{(1,5)} = 0.18$, $p = .69$) influenced the spatial variability significantly, and the interaction between them was also not significant ($F_{(2,10)} = 1.82$, $p = .21$). Both the influence of the feedback condition on judged reachability and its effect on the spatial error in depth are about 10 cm, which is the distance between the two feedback distortions.

To illustrate this we present a top view of the performance of a representative subject, both when feedback was shifted away (Fig. 5A) and when it was shifted closer to the body (Fig. 5B). The lines indicate the target's paths on trials in which the subject did not move. Here we see the difference in judged reachability (the lines are nearer in panel B) and in the spatial errors (the endpoints in panel B overlap considerably with the lines that represent paths that were judged to be unreachable). The fact that the finger often ended beyond the blue curve indicates that this subject leaned further forward for intercepting the targets than when initially indicating how far he/she could reach. Comparing the locations at which the finger movements ended (dots in Fig. 5) with the blue curves indicating the true limits of reachability shows that the central endpoints when the feedback was close to the body were clearly nearer to the blue line (some of them even overlap with

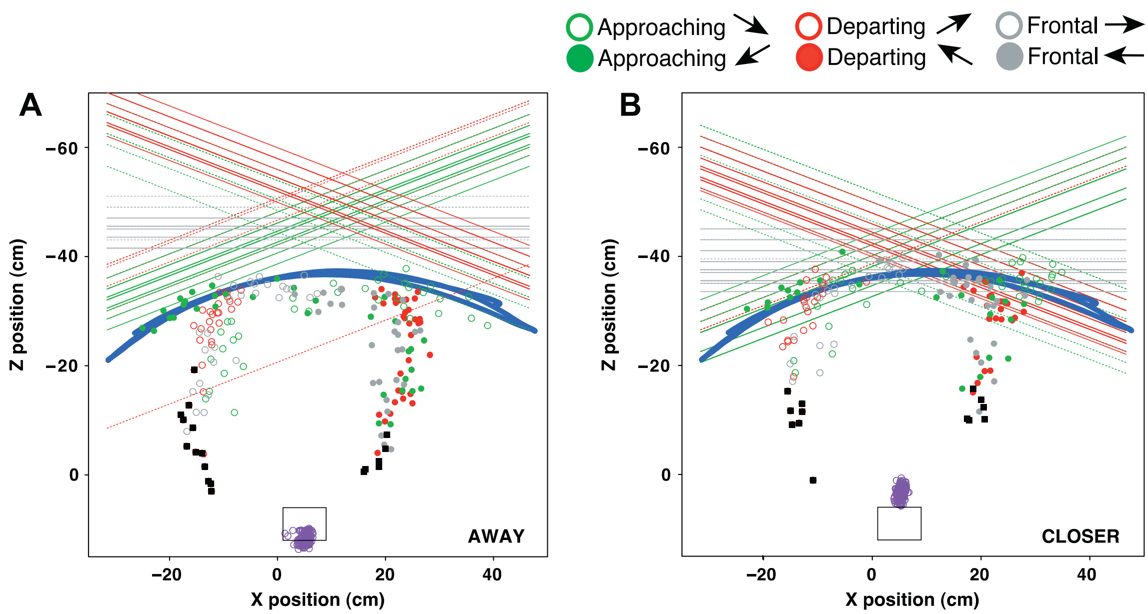

Fig. 5. Overview of various values for a representative subject. The reaching range of the arm is represented by the blue line. Purple dots are the starting positions of the finger. Other symbols indicate the final position of the finger. Colors indicate the direction of the target's path (see Legend). Trials in which the reaction time was shorter than 700 ms are shown as black squares (removed from the analysis) to indicate that the position at which the target was intercepted is likely to have been limited by the reaction time rather than by judgments of when the target came within reach. Lines indicate target trajectories on trials in which the hand did not move. (A) Condition in which the feedback was 5 cm further away than the finger. (B) Condition in which the feedback was 5 cm closer than the finger. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

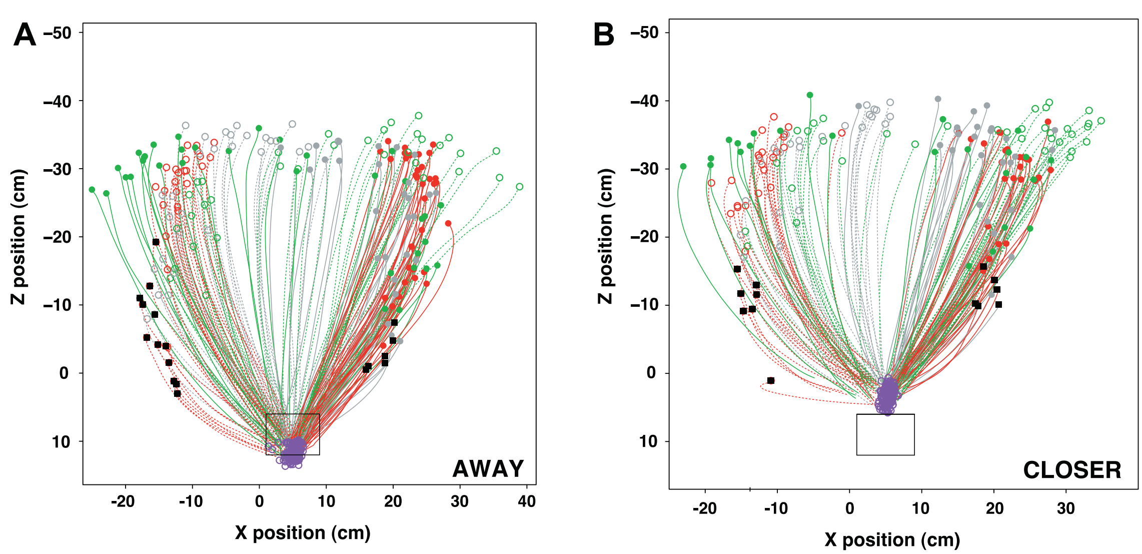

Fig. 6. Top view of the hand trajectories of a representative subject for the feedback distortion 5 cm away from the finger (A) and for 5 cm closer to the body (B). Green lines correspond to hand movements performed towards approaching objects, red lines for departing and grey lines for objects moving in the frontal plane. Open dots and dotted lines represent targets moving from left to right and solid dots and lines represent targets moving from right to left. Black squares were the trials removed from the sample, as in the previous analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

it), whereas the endpoints when the distortion was away were well below the true reachability indicating a shorter extension of the hand movement because of the adaptation to the away feedback distortion.

Fig. 6 shows the corresponding hand trajectories of the final hand endpoints represented in Fig. 5. Moving to the same endpoints means that the subject had to move his or her hand further when the feedback was shifted further from the body than when the feedback was shifted closer. However, the Z coordinate of the final hand position was found to be 5 cm further when the shift of the feedback was close to the body (away: −29.1 cm, closer: −33.7 cm, $F_{(1,5)} = 16.94$, $p < .01$). Given the fact that the gap between the starting positions of the two feedback distortions was 10 cm, the amplitude of the hand movement was then 5 cm larger when the feedback distortion was away from the body (away: 43.7 cm, closer: 38.8 cm, $F_{(1,5)} = 16.1$, $p = .01$). Neither the Z value of the hand endpoint ($F_{(2,10)} = 0.15$, $p = .86$) nor the euclidian distance of the hand movement ($F_{(2,10)} = 1.4$, $p = .29$) differed significantly as a function of the direction of the movement. Interactions were not significant.

4. Discussion

In this study, we wanted to investigate the influence of shifting the visual feedback of the hand's position on reachability estimates during movements towards a moving object. Our task required continuous visual estimation of the object's motion relative to the observer's body in order to judge where and when the object will be at a reachable position, as well as motor planning and execution of the hand movement. These aspects introduced temporal restrictions that were absent in studies that only involved perceptual judgments (de Grave, Brenner, & Smeets, 2011a).

From the results of our experiment, it is clear that a forward shift of the visual feedback of the hand resulted in an increase of the judged reachability. Quantitatively, the magnitude of the effect was approximately the distance between the two feedback shifts (10 cm). Hence, we replicated the effect on reachability estimations that de Grave, Brenner, and Smeets (2011a) found for static objects with a temporally restricted reaching movement towards a moving target. Data are also consistent with studies that reported moving objects to be judged as reachable when they are more distant than if they are static (Rochat & Wraga, 1997), since the magnitude of our feedback effect was higher than in de Grave's study. In contrast, our findings are not in agreement with different reachability judgments for different directions of stimulus motion, such as objects to be reachable at larger distances when the object moved towards the observer (Delevoye-Turrell, Vienne, & Coello, 2011; Fischer, 2000). The difference may lie in the way the data are analyzed, in that we consider the inevitable delays during motor planning and execution of the movement. These delays imply that the hand must start moving towards an approaching object when the object is still unreachable in order to intercept the object as soon as it becomes reachable. Interception of departing objects must occur before they become unreachable. In studies based on perceptual judgments of rechability, the task did not involve moving but participants were instructed to say 'stop' when they thought they could reach the object that was moved by the experimenter (Fischer, 2000). Thus the difference may be that our participants had to take into account the time they themselves spent performing the hand movement, rather than accounting for the experimenter's reaction time and movement. This view is endorsed by the lack of differences between approaching and departing objects looking at the target position at the end of the hand movement, whereas approaching objects were considerably further at the onset. Consequently, we suggest that participants estimated an 'interception region' independent of the stimulus direction, relying on the time needed to perform a reaching movement to the object at this region.

Our results also confirm that hand movements are fairly fully adjusted to feedback distortion (Bourgeois & Coello, 2012). In fact, in this study the change in judged reachability was even slightly larger than the imposed shifts. This is not as strange as it may seem because the change in judged distance with simulated distance is probably underestimated (Sousa, Brenner, & Smeets, 2011; Sousa, Brenner, & Smeets, 2010). As a result of this complete adaptation to the distortion, the spatial accuracy when intercepting the target was conditioned to the amplitude of the movement in a way that participants with longer movements committed higher spatial errors, as reported in previous studies (Sarlegna & Blouin, 2010). Also, the shorter extension of the arm when the feedback distortion was away from the body resulted in higher spatial errors in the depth axis, suggesting that the hand visual feedback takes part in the control of the movement amplitude together with the visual information of the target (Brenner & Smeets, 2003) and the proprioceptive feedback mechanisms (Bagesteiro, Sarlegna, & Sainburg, 2006).

In sum, these results suggest that participants' judgments are completely adapted to the shifts in feedback that we imposed. The critical influence of the hand visual feedback on the reachability estimates and on their underlying actions also states the importance of the visual information as the prominent sensory input (Desmurget et al., 1995). Participants judged targets to be reachable in accordance with whether the feedback cube could reach the target rather than whether the finger could reach the target. This is consistent with earlier reports that tools can affect judgments of reachability. Our task expands on previous studies of judged reachability in showing that the adjustments to what is judged to be reachable are reflected in many aspects of our actions.

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