Effect of visuomotor calibration and uncertainty on the perception of peripersonal space

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Published online: 12 June 2012
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Abstract Target selection for action depends not only on the egocentric location of objects estimated from retinal and extraretinal variables, but also on the assessment of current action possibilities. In the present study, we investigated the effect of altering sensorimotor anticipation processes on subsequent perceptual estimates of reachability. To do so, we conducted two experiments in which we changed the relation between visual distance and movement amplitude. Experiment 1 showed that iterative visuomotor adaptation to distorted visual feedback (in steps of ± 15 mm, up to a total adaptation of ± 75 mm) led to a congruent variation of perceived reachable space, although the first introduction of the shifted visual feedback produced a reduction of perceived reachable space whatever the direction of the feedback shift. Experiment 2 showed that increasing uncertainty about visuomotor performances, by providing a visual feedback randomly shifted in depth (± 7.5 mm), produced the same reduction of perceived reachable space in the absence of visuomotor adaptation. Taken together, these data suggest that the visual perception of reachable space depends on a motor-related perceptual system, which is affected by both visuomotor recalibration and reliability of the visuomotor system.

Keywords Perception · Visuomotor recalibration · Reachability · Peripersonal space · Variability

Introduction

The way we perceive our spatial environment in relation to our body and action system is a topic of fundamental importance in everyday life and a widely debated theoretical issue in psychology and cognitive neuroscience. Since Berkeley's famous essay on vision (Berkeley, 1709/1732), theorists of perception from different disciplines have defended the idea that the experience of spatiality may proceed from an interpretation of sensory information through reference to the possibilities of action (e.g., Bergson, 1896/1912; Gibson, 1979; Husserl, 1907/1973; Merleau-Ponty, 1945; Poincaré, 1907/1921). To date, convincing arguments in the empirical sciences have been provided supporting the view that the perception of the external world is under the influence of, or even scaled by, action-specific constraints (Barsalou, 2008; Fajen, 2005; Gallese, 2007; Witt & Proffitt, 2008), when, for instance, walking through obstacles (Warren & Whang, 1987), climbing stairs or hills (Bhalla & Proffitt, 1999; Warren, 1984), or manually interacting with objects (Carello, Groszofsky, Reichel, Solomon, & Turvey, 1989; Witt, Proffitt, & Epstein, 2004).

With regard to the latter situation, acting toward objects depends on our ability to discriminate the area of space in which objects can be easily reached (the peripersonal space) from the space in which they are beyond our sphere of influence (the extrapersonal space), thus requiring a transfer of the body to accomplish a given action (Cutting & Vishton, 1995; Previc, 1998). In the past, many studies have shown that people are quite accurate in visually delimiting their peripersonal space (e.g., Bootsma, Bakker, van Snippenberg, & Tdlohreg, 1992; Bourgeois & Coello, 2009; Carello et al., 1989; Coello & Iwanow, 2006; Fischer, 2000; Gabbard, Ammar, & Lee, 2006; Rochat & Wraga, 1997), although perceptual estimates

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of reachability have been found to be influenced by environmental context (Coello & Iwanow, 2006), emotional state (Kennedy, Gläscher, Tysza, & Adolphs, 2009), and postural constraints (Fischer, 2000; Gabbard, Cordova, & Lee, 2007; Rochat & Wraga 1997), as well as mental or neurological illness (Coello & Delevoye-Turrell, 2007; Delevoye-Turrell, Vienne, & Coello, 2011).

The fact that reachability estimates are influenced by postural constraints has led to the suggestion that peripersonal space is perceived as a function of and in relation to anticipated action possibilities (Coello & Delevoye-Turrell, 2007; Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010), elaborated from past experiences about the opportunities, effects, and costs of acting in the environment (Fajen, 2005; Previc, 1998; Proffitt, 2006). Evidence for the contribution of motor-related information in the perception of reachable space is supported mainly by the observation that the neural network involved in the perception of nearby objects (Caggiano, Fogassi, Rizzolatti, Their, & Casile, 2009; Gollwitzer, Cavina-Pratesi, & Culham, 2009; Grezes, Tucker, Armony, Ellis, & Passingham, 2003) or reachability judgments (Bartolo et al., 2009) includes brain areas that overlap with those recruited for actual motor planning and execution. The involvement of brain motor areas in the perception of reachability was furthermore supported by the effect of depressing the cortical excitability of the motor cortex while a reachability judgment task was performed. By using transcranial magnetic stimulation (TMS) at low frequency, Coello et al. (2008) found an interference effect in a reachability judgment task when TMS was applied over the left motor cortex, which was not observed when TMS was applied over the left temporo-occipital area used as a control site.

The perception of reachable space is, then, thought to depend on a motor-based perceptual system combining visual variables with motor-related information. According to this view, it is assumed that objects in nearby space are automatically coded in a motor format, so that the consequences of acting toward these objects can be anticipated and action feasibility can be evaluated (Gallese, 2007; Jeannerod, 2006). Anticipating the consequences of potential motor actions is thought, then, to represent the mechanism subtending the perceptual distinction between reachable and nonreachable objects (Coello & Delevoye-Turrell, 2007; Jeannerod, 2006). In the same vein, Witt and Proffitt (2008) proposed that motor simulation represents the mediator of action-specific influences on perception. According to this approach, internal motor simulation is thought to provide access to information about a person's ability to perform an intended action (Bidet-Ildei, Sparrow, & Coello, 2011; Fajen, 2005; Witt & Proffitt, 2005), to the anticipated outcome and the energetic costs associated with this particular action (Proffitt, 2006), and finally to the

expected changes in the environment following action completion (Witt et al., 2004).

To further investigate the action-dependent perception of reachable space, we evaluated the effect of altering the relation between visual distance and corresponding motor parameters on the perception of peripersonal space. To do so, we designed a manual reaching task in which participants were required to adapt their motor responses in order to compensate for a shift of the visual feedback presented at the movement end point. Several studies have shown in the past that introducing a small distortion in the sensory feedback about motor performance led to an unconscious adaptation of the motor response so as to reduce the mismatch between actual and intended sensory signals (Bernier, Chua, & Franks, 2005; Clower & Boussaoud, 2000; Cressman & Henriques, 2010; Magescas & Prablanc, 2006; Magescas, Urquizar, & Prablanc, 2009; Serrien & Spapé, 2011; Wong & Henriques, 2009). Using a sensorimotor recalibration paradigm, Mon-Williams and Bingham (2007), for instance, showed that the relation between visual distance and reach distance can be modified by providing distorted feedback. The rationale for our study was that if space perception relies on motor anticipation processes, modifying the relation between visual target distance and reach movement should affect the perceived reachable space. In the present study, visual information about movement end point was displaced in steps of 15 mm in the far (shift-away group) or near (shift-toward group) space across six consecutive trial blocks, resulting in a total discrepancy of ± 75 mm between movement end point and target location at the final stage of the adaptation period. In addition to the shift of visual feedback, target location was also displaced by 15 mm in every block of trials, so that movement amplitude after adaptation remained unchanged across the whole experiment. This experimental design ensured that any change in the perceived reachable space would be related to the modified relation between perceived visual location and the corresponding motor response, and not to any variation of the kinematic parameters associated with motor responses. In the control group (no-shift group), no feedback shift was introduced. Consequently, after adaptation, depending on the group, similar movement amplitude corresponded to a closer (shift-toward group), farther (shift-away group), or unchanged (no-shift group) target location. Assuming that motor-related information contributes to the perceptual judgment of reachable space, we expected a variation of perceived reachable space of similar amplitude and direction as the visuomotor adaptation. More precisely, performing the same action toward a visual target located at a closer distance should induce a reduction of perceived reachable space. The opposite result was expected when a similar action toward a visual target located at a farther distance was performed.

To anticipate, we found that the variation of perceived reachable space was congruent with the visuomotor adaptation,

although a contraction bias of perceived reachable space was observed in the first block of trials of visuomotor adaptation whatever the direction of the visual feedback shift. Consequently, in [Experiment 2](#), we tested the effect of increasing the variability of the visuomotor system on reachability estimates by randomly shifting the visual feedback about movement end point, with no adaptation requirement. We found a similar contraction bias of the perceived reachable space, suggesting that the latter depends on a motor-related perceptual system, which is affected by both visuomotor recalibration and the reliability of the visuomotor system.

Experiment 1

The aim of this experiment was to evaluate whether modifying the relation between visual distance and corresponding movement amplitude (while maintaining the kinematic parameters of motor response) would result in a congruent change of the perceived reachable space. The discrepancy between target visual information and movement amplitude was achieved by iteratively shifting the visual feedback about movement end point in steps of 15 mm across six consecutive blocks of trials, requiring then a total visuomotor adaptation of 75 mm. Assuming that perceived reachable space relies on an action-related perceptual system, the boundary of perceived reachable space was expected to progressively shift across the blocks of trials, congruently with the amplitude and direction of the visuomotor adaptation.

Method

Participants The present experiment involved 30 healthy participants (15 males and 15 females), with normal or corrected-to-normal vision, whose ages ranged from 18 to 30 years (mean age = 24.8, $SD = 3.1$). They were self-declared volunteers and gave their informed consent prior to their inclusion in the experiment. They were all right-handed, as assessed by self-report from a ten-item questionnaire adapted from the Edinburgh Handedness Inventory (Oldfield, 1971; the mean laterality quotient was .94, with a range from .79 to 1). Participants were randomly assigned to one of the three groups involved in the experiment (no shift, $n = 10$; shift away, $n = 10$; shift toward, $n = 10$).

Apparatus The experimental apparatus consisted of a rectangular box (60 cm high, 100 cm wide, and 70 cm deep) with the inside divided horizontally by a mirror (see [Fig. 1a](#)). A 20-in. computer monitor was placed upside-down on the top surface of the apparatus so that the image generated by the computer was reflected in the mirror and, due to optical geometry, the image from the computer screen projected onto the bottom surface of the

apparatus corresponding to the workspace. The mirror was positioned so that the hand was visible at the starting position, but not following movement onset. In order to minimize the participant's ability to use visual cues in the form of reflections from the upper half or the side of the box, the internal surfaces of the box were smooth and painted matt black. No visual information from the external environment was available during the entire experimental session.

The maximum reachable distance was initially estimated within the experimental box for each participant by measuring the distance the participant could reach with the right arm fully stretched out. In the experiment, several visual targets (green dots of 10-mm diameter) were presented along the sagittal body-midline axis, each of them being presented on a dark background. Two target sets were used according to whether the perceptual or the motor task was performed. In the perceptual task, 31 visual targets were randomly presented along the sagittal axis at distances from 110 mm up to 410 mm from the starting position used in the motor task, with an intertarget distance of 10 mm. In the motor task, 5 targets were presented along the sagittal axis. Three of these targets (adaptation targets) were positioned at 80, 110, and 140 mm, respectively, from the maximum reachable distance in the direction of the participant. They were used to allow the participants to calibrate their motor responses on the basis of the visual feedback provided at movement end point (blue dot of 10-mm diameter). The 2 other targets (test targets) were used for evaluating, during the last 12 trials of each motor session, the adaptation of the visuomotor system to the shifted visual feedback (from 0 mm up to 75 mm; see below). They were initially presented at 95 and 125 mm from the maximum reachable distance in the direction of the participant, and movements toward these targets never received any visual feedback (see [Fig. 1b](#)).

Procedure In the motor task, participants were taught to move an electromagnetic stylus horizontally on a digitizer tablet, so that its final position overlapped with the visual target. A trial started when the electromagnetic stylus was positioned on the starting location (about 23 cm from the body). A target then appeared, following a 500-ms delay, and disappeared at movement offset when stylus velocity dropped under 5 cm/s for more than 500 ms. In the perceptual task, participants provided reachability estimates for visual targets presented at different distances. The target appeared 500 ms after the participants pressed the space bar of the computer keyboard placed on their lap and disappeared when the participants' response was given. To allow for visual adaptation to the dark room, participants were familiarized with the various response conditions (perceptual and motor tasks) during a period of about 15 min; then they began with the first block of trials of the two experimental tasks.

Fig. 1 **a** Schematic representation of the experimental apparatus. The bottom part of the apparatus was visible only through optical projection on the mirror of information coming from the upper part. The hand was visible only at the starting location. **b** Visual targets used in the motor and perceptual tasks. **c** Schematic representation of the variation of target location in the shift-toward, the shift-away, and the no-shift groups across the blocks of trials (B1–B6), considering a single target location. In all groups, similar movement amplitude was required

despite the variations of target location depending on the shift of the visual feedback. **d** Schematic representation of the procedure used in Experiment 2 for the random-shift group. In the first block of trials, feedback location corresponds to actual finger location. In the second block of trials, feedback location was randomly shifted in depth by ± 7.5 mm according to finger location, suggesting an increase of visuo-motor variability

Participants performed six successive blocks of 184 trials. Each block of trials consisted of the motor task (60 trials), followed by the perceptual task (124 trials). In the motor task, participants were requested to reach the displayed target as quickly and accurately as possible with their right hand. Movements were initially performed toward the adaptation targets at 80, 110, and 140 mm from the maximum reachable distance (48 trials, randomly presented). Visual feedback about movement end point was provided every trial during the first 24 trials, whereas during the last 24 trials, it was provided every 2 trials on average, which allowed for efficient adaptation (Bingham, Coats, & Mon-Williams, 2007). The feedback was available for 500 ms after the target disappeared, the hand being still on the final

location. In the blocks of trials 2–6, the position of the visual feedback was shifted by +15 mm in the shift-away group or by –15 mm in the shift-toward group, as compared with the previous block of trials, up to a displacement of ± 75 mm in the sixth block of trials. Targets position was also shifted across the blocks of trials, in the same direction and amplitude as the visual feedback (± 15 mm), in order to keep the amplitude and direction of reaching movements unchanged during the whole experiment (see Fig. 1c). For instance, in the shift-away group, a participant programmed a movement toward the target located at –10 cm from the maximum reachable distance (say, 50 cm from the body). In the first block of trials, the participant reached this location, and the terminal feedback indicated that the movement end point

overlapped with the target location. In the second block of trials, the target was displaced by 15 mm (51.5 cm from the body), and when the participant reached the target, the terminal feedback indicated that the movement end point was 15 mm farther than the target location. The participant had to reduce his/her movement amplitude by 15 mm so that the location of the feedback remained coincident with the target location. Since the target was now located at 51.5 cm from the body, he/she would now perform a 50-cm reaching movement, which is exactly what he/she was doing during the first block of trials. This procedure was repeated in the remaining blocks of trials until the gap between movement end point and target location reached 75 mm. In the no-shift group, the visual feedback was accurate during the whole blocks of trials, and no displacement of the targets was introduced. This experimental design was used to ensure that participants performed movements with the same amplitude during the whole experiment, whatever the group they were assigned to. Thus, manual reaching movements were consistently performed at the same distance with respect to the actual limit of reach, despite the fact that the targets were presented at different distances. Following the set of 48 trials in each block of trials, 12 trials were performed requiring the participant to reach toward the two test targets used to evaluate the current visuomotor calibration (95 and 125 mm from the maximum reachable distance), with no feedback provided at movement end point.

The perceptual task was performed following each repetition of the motor task, and the 31 targets were presented 4 times in a random order in each of the six blocks of trials. Participants had to estimate whether the target presented was reachable with their right hand or not, without having the possibility to actually move their upper limb. This two-alternative forced choice task (reachable–unreachable) was performed by the participants pressing, with the left hand, one of the two prespecified keys on the computer keyboard (counterbalanced across participants). Participants' right hand was positioned in front of them on the sagittal axis and remained still during the whole experiment.

Following the successive periods of visuomotor adaptation, we expected no effect of adaptation on the kinematic parameters of manual reaching movements, whatever the group. However, due to the induced change of the relation between target position and movement parameters, we expected a displacement of the boundary of perceived reachable space of about 15 mm following each visuomotor adaptation period. The shift was expected to result in an extension of perceived reachable space for the shift-away group (farther target location for similar movement amplitude) and a reduction of perceived reachable space for the shift-toward group (closer target location for similar movement amplitude). No shift was expected in the no-shift group (same target location for unchanged movement amplitude).

Data recording and processing In the *motor task*, (x, y) trajectories were registered from the coordinates provided by the digitizer tablet (Wacom UD-1825; temporal resolution, 100 Hz; spatial resolution, 0.1 mm). Spatial and temporal performances were analyzed on the last 12 trials of each block of trials, corresponding to the set of targets for which no feedback about movement end point was provided. End point positions of individual movements were used to compute spatial terminal errors according to the targets' location. In relation to our working hypothesis, constant errors were decomposed into radial (performance in amplitude) and angular (performance in direction) errors. Radial error was evaluated from the difference between movement vector length and target vector length, with a vector origin at the movement starting location (a negative sign was used to indicate undershooting). Angular error corresponded to the angle between the starting-position-to-target vector and the starting-position-to-end-movement-position vector (a negative sign was used for indicating deviations to the right of the target). The kinematic (peak velocity) and temporal (reaction time, movement time, percentage of time taken by the acceleration and deceleration periods) parameters were also examined from hand path. These parameters were estimated essentially to evaluate whether visuomotor recalibration affected the temporal and kinematic properties of manual reaching movements. Performances relating to the different target locations were pooled for statistical investigations, which were carried out on all dependent variables.

In the *perceptual judgment task*, reachability judgments and response times (RTs) were registered by the computer. The perceived boundary of reachable space was determined using a maximum likelihood fit procedure based on the second-order derivatives (quasi-Newton method) to obtain the logit regression model that best fitted the reachable/unreachable responses of the participants for the 31 positions of the target, using the following equation:

$$y = e^{(\alpha + \beta X)} / (1 + e^{(\alpha + \beta X)})$$

in which y was the participant's response, X corresponded to the distance, and $(-\alpha / \beta)$ was the critical value of X at which the transition from one type of response (reachable) to the other type of response (unreachable) occurred, thus expressing the perceived maximum reachable distance. The discrimination threshold was defined as the distance between the critical value of X at which the transition from one type of response to the other type of response occurred and the critical value of X at which the probability associated with the logit function was .84 (Ernst & Banks, 2002). A smaller discrimination threshold indicated an easier separation between reachable and unreachable responses for the participant.

We analyzed RT in the perceptual judgment task by fitting the variation of RT according to target's location, using a

Gaussian regression model. Indeed, previous studies revealed that RT usually increases when one approaches the stimuli corresponding to the transition between one possible response (e.g., reachable) and the alternative response (e.g., unreachable; Delevoye-Turrell et al., 2011; see also Hirose, Hagura, Matsumura, & Naito, 2010). Accordingly, maximum RT was expected to occur when the target was presented close to the boundary of reachable space. We then computed the coefficient (r) measuring the correlation between the distance corresponding to the boundary of reachable space and the distance corresponding to maximum RT.

Statistical analyses were carried out separately for the perceptual and the motor tasks on the different variables through a two-way analysis of variance (ANOVA: *block of trials* [B1, B2, B3, B4, B5, B6] $\times$ *group* [no shift, shift toward, shift away]) with repeated measures on the first factor only. Normality of performance distribution and homoscedasticity were tested for the different groups in the first block of trials. Furthermore, in case the sphericity assumption was violated (i.e., epsilon smaller than 1), Huyn–Feldt adjustments of the p -values were reported.

Results

Mean arm length, as measured by the distance between the shoulder joint (about 45 cm above the workspace) and the tip of the index finger while the arm was extended was 66.8 cm. Thus, the average maximum reachable distance on the workspace was located at 49.4 cm from the body and at 26.4 cm from the starting position of the hand along the sagittal axis.

Motor task

Reaction time In the motor task, reaction time was, on average, 491 ms ($SD = 172$ ms). It was not affected by group, $F(2, 27) = 1.47$, $p = .25$, or by block of trials, $F(5, 135) = 0.82$, $p = .53$. There was also no interaction between the two factors, $F(10, 135) = 0.57$, $p = .83$ (see Table 1 for a detailed presentation of the data).

Spatial performance Radial error when the motor task was performed was, on average, 0.07 mm ($SD = 35.1$ mm) relative to actual target location and did not differ across the blocks of trials, $F(5, 135) = 1.34$, $p = .25$. We found, however, an effect of group, $F(2, 27) = 317$, $p < .01$, and an interaction between group and block of trials, $F(10, 135) = 105.4$, $p < .01$. Simple effects associated with the interaction indicated that radial error was not dependent on the group in block 1, $F(2, 27) = 0.35$, $p = .71$ (for the shift-toward group, -2.1 mm [$SD = 13.5$ mm]; for the shift-away group, -1.3 mm [$SD = 12.7$ mm]; for the no-shift group, -5.3 mm [$SD = 5.5$ mm]), but depended on the group in blocks 2–6 [$F(2, 27) = 35.5$, $F(2, 27) = 71.8$, F

(2, 27) = 219.6, $F(2, 27) = 592.9$, and $F(2, 27) = 337.9$, respectively; all $ps < .01$; see Table 1]. Figure 2a, b shows that, as was expected, radial error increased positively across the blocks of trials in the shift-toward group (the variation of performance between blocks 1 and 6 was 71.6 mm), $t(9) = 14.2$, $p < .01$, and negatively in the shift-away group (the variation of performance between blocks 1 and 6 was -68 mm), $t(9) = 16.7$, $p < .01$, and did not vary significantly in the no-shift group (the variation of performance between blocks 1 and 6 was 6.1 mm), $t(9) = 2.27$, $p > .05$. Interestingly, Fig. 2b shows that only a few trials were needed in each block of trials for the participants to adapt to the shifted visual feedback, since the introduced distortion was small and did not modify drastically the relation between visual distance and movement amplitude specified in the previous block of trials.

Angular error was 0.9° ($SD = 3.16^\circ$), on average, and was not affected by group, $F(2, 27) = 0.43$, $p = .65$. There was also no effect of block of trials, $F(5, 135) = 1.82$, $p = .11$, and no interaction between the two factors, $F(10, 135) = 0.79$, $p = .63$. Thus, hand trajectory ended consistently slightly to the left of the target for all groups and during the whole blocks of trials (see Table 1).

Temporal and kinematic parameters The duration of manual reaching movements was, on average, 888 ms ($SD = 279$ ms) and was not affected by group, $F(2, 27) = 2.13$, $p = .14$. It varied only slightly in the successive blocks of trials, $F(5, 135) = 2.29$, $p = .05$ (for block 1, 845 ms; for block 2, 881 ms; for block 3, 898 ms; for block 4, 892 ms; for block 5, 907 ms; for block 6, 905 ms), but there was no interaction between the two factors, $F(10, 135) = 1.45$, $p = .17$. There was no effect of visuomotor adaptation on the maximum velocity reached during hand transport (on average, 0.34 m.s $^{-1}$, $SD = 0.11$ m.s $^{-1}$) when the different groups were considered, $F(2, 27) = 2.42$, $p = .11$, or blocks of trials, $F(5, 135) = 1.15$, $p = .37$, and there was no interaction between the two factors, $F(5, 135) = 0.95$, $p = .49$. The percentage of time taken by the acceleration period was 41.9 % ($SD = 6.7$ %), and thus, 58.1 % for the deceleration period. It was not affected by group, $F(2, 27) = 0.48$, $p = .62$, and did not vary across blocks of trials, $F(5, 135) = 0.67$, $p = .65$. There was also no interaction between the two factors, $F(5, 135) = 1.05$, $p = .40$. Consequently, the intrinsic characteristics of reaching movements remained unchanged across the blocks of trials in the three groups, and they were thus not affected by the iterative visuomotor adaptation.

Perceptual judgment task

Response time In the perceptual judgment task, RT was, on average, 731 ms ($SD = 137$ ms). It was not affected by group, $F(2, 27) = 0.04$, $p = .96$. There was, however, an

Table 1 Means and standard deviations in [Experiment 1](#) for the location of perceived reachability limit (Boundary), discrimination threshold (DT), response time (RT), distance corresponding to the peak of response time (dRT) in the perceptual task, and for radial error (Rad.

Err.), angular error (Ang. Err.), reaction time (RT), movement time (MT), peak velocity (PV), and percentage of movement time taken by the acceleration period (DAP) in the motor task

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
No Shift						
Perceptual task						
Boundary (mm)	20.9 (28.7)	15.5 (31.3)	8.1 (32)	4.4 (36.4)	4.3 (34.1)	7.8 (33.3)
DT (mm)	17.3 (7.2)	20 (12.4)	12 (10.3)	12.4 (7.7)	17.9 (13.2)	15.6 (8.1)
RT (ms)	835 (111)	748 (95)	726 (62)	691 (59)	682 (68)	660 (70)
dRT (mm)	20.6 (30.4)	20.4 (28.3)	4.8 (34.7)	−0.3 (53)	−0.2 (35.8)	4.7 (43.3)
Motor task						
Rad. Err. (mm)	−5.3 (5.5)	−3.2 (5.6)	1.4 (8.4)	6.3 (9)	4.5 (7)	0.9 (7.6)
Ang. Err. (deg)	0.8 (3.8)	0.4 (3.1)	0.6 (3.5)	1.3 (3.6)	0.7 (2.5)	0.5 (3)
RT (ms)	429 (98)	416 (89)	434 (65)	430 (111)	443 (91)	424 (106)
MT (ms)	730 (110)	729 (94)	747 (103)	746 (102)	760 (139)	801 (157)
PV(mm/s)	323 (125)	315 (110)	336 (131)	356 (152)	349 (148)	316 (114)
DAP (%)	41.3 (6.2)	41.2 (3.7)	41.2 (4.7)	41.2 (5.4)	42.7 (8.1)	40.8 (7.2)
Shift Away						
Perceptual task						
Boundary (mm)	20.9 (38.9)	−6.5 (35.5)	2.1 (29.5)	5 (29.6)	19.2 (34.7)	31.8 (30.6)
DT (mm)	13.7 (4)	9.3 (8)	13.2 (7.4)	14.9 (7.1)	11.8 (9.2)	13 (7.8)
RT (ms)	829 (177)	782 (169)	723 (161)	696 (135)	692 (168)	666 (123)
dRT (mm)	25.7 (59.3)	−8.9 (40.2)	−0.3 (48.7)	14.4 (46.7)	29.2 (34)	33.6 (31.5)
Motor task						
Rad. Err. (mm)	−1.3 (12.7)	−14.1 (8)	−24.4 (11.3)	40.2 (10.1)	−55 (8)	−69.7 (7.8)
Ang. Err. (deg)	2.1 (4.2)	2.1 (3.2)	1.5 (3.1)	−1.9 (2.8)	0.8 (3.1)	0.9 (3.8)
RT (ms)	514 (152)	508 (212)	510 (198)	504 (511)	513 (190)	496 (149)
MT (ms)	851 (185)	933 (231)	991 (310)	949 (233)	925 (228)	929 (235)
PV(mm/s)	320 (83)	282 (47)	297 (76)	287 (69)	289 (58)	291 (72)
DAP (%)	43.1 (4.2)	43.3 (5.6)	43.1 (7)	44 (5)	43.8 (4.2)	43.8 (5.2)
Shift Toward						
Perceptual task						
Boundary (mm)	29.8 (40.8)	−7.6 (46.7)	−22.2 (47.6)	−39.5 (50.5)	−60 (65.5)	−60.1 (64.1)
DT (mm)	15.9 (8)	12.6 (7.8)	16.6 (8.9)	13.8 (8.5)	13.4 (12.5)	15 (8)
RT (ms)	851 (143)	789 (162)	747 (143)	713 (125)	675 (121)	661 (140)
dRT (mm)	14.8 (74)	−17.2 (57.3)	−18.5 (58.7)	−26.3 (68.8)	−61.4 (70.4)	−56.6 (63.1)
Motor task						
Rad. Err. (mm)	−2.1 (13.5)	15 (9.3)	25.5 (7.9)	39.5 (6)	54 (6.2)	69.6 (17.7)
Ang. Err. (deg)	1.4 (2.6)	1.7 (2.4)	0.3 (2.3)	0 (2.6)	−0.7 (4.8)	0.1 (2.5)
RT (ms)	611 (362)	541 (169)	553 (206)	519 (170)	518 (169)	481 (120)
MT (ms)	955 (305)	982 (383)	957 (388)	981 (382)	1035 (448)	986 (410)
PV(mm/s)	388 (86)	376 (73)	428 (183)	375 (85)	380 (102)	380 (121)
DAP (%)	43.6 (6.2)	41.8 (8.4)	40 (8.4)	40.4 (9.4)	40.2 (10)	39.6 (9.8)

effect of block of trials, $F(5, 135) = 38.64$, $p < .01$, with a progressive decrease of RT across the successive blocks of trials (block 1, 838 ms; block 2, 773 ms; block 3, 732 ms; block 4, 700 ms; block 5, 683 ms; block 6, 662 ms). However, no interaction was observed between the two factors, $F(10, 135) = 0.38$, $p = .95$.

Boundary of perceived reachable space The boundary of reachable space was perceived, on average, at −1.5 mm ($SD = 47$ mm) with respect to the actual maximum reachable distance. Radial error in reachability estimates was dependent on group, $F(2, 27) = 3.36$, $p = .04$ (for the shift-away group, 12.1 mm [$SD = 34.5$ mm]; for the shift-toward group,

Fig. 2 **a** Mean radial errors (in millimeters) and standard errors for the shift-toward (black), shift-away (gray), and no-shift (white) groups in the six blocks of trials when the motor task was performed, according to actual target distance (0 value). **b** Mean radial errors (in millimetres)

for the shift-toward (black), shift-away (gray), and no-shift (white) groups for all trials when the motor task was performed, according to actual target location (0 value). Each dot represents the average radial error for each trial in each group

−26.6 mm [$SD = 60.1$ mm]; and for the no-shift group, 10.2 mm [$SD = 31.9$ mm]; see Fig. 3a). Radial error in reachability estimates was also dependent on block of trials, $F(5, 135) = 16.67$, $p < .01$ (for block 1, 23.8 mm; block 2, 0.5 mm; block 3, −4 mm; block 4, −10 mm; block 5, −12.2 mm; block 6, −6.8 mm). Furthermore, an interaction was observed between the two factors, $F(10, 135) = 14.74$, $p < .01$. This interaction was due to the fact that the boundary of perceived reachable space shifted toward the participant in the shift-toward group, $F(5, 45) = 25.02$, $p < .01$, whereas it shifted away from the participant in the shift-away group, $F(5, 45) = 7.21$, $p < .01$, and did not vary in the no-shift group, $F(5, 45) = 2.46$, $p < .05$. However, a similar performance was observed in the shift-toward and shift-away groups during the two first blocks of trials (see Fig. 3a). In the first block of trials (no-adaptation condition), the different groups showed the same performance while providing reachability estimates, since no visuomotor adaptation was required, $F(2, 27) = 0.20$, $p = .82$. Surprisingly, in the second block of trials, participants adapted similarly to the shifted visual feedback, whatever the direction of the feedback shift, $F(2, 27) = 1.15$, $p = .33$. More specifically, a reduction of perceived reachable space was observed, whereas the shift of the visual feedback was directed away from (shift-away group) or toward (shift-toward group) the perceiver, $t(9) = 0.06$, $p = .95$. However, except for the second block of trials, we observed that the variations of perceptual performances were, overall, in agreement with the iterative visuomotor adaptation to the 15-mm shift of the visual feedback (all $ps > .10$ when the observed and predicted spatial errors were compared), except in the block of trials 4 for the shift-away group and in the block of trials 6 for the shift-toward groups, where perceptual shift was slightly inferior to

the visuomotor adaptation, $t(9) = 3.03$, $p = .01$, and $t(9) = 3.13$, $p = .01$, respectively.

The discrimination threshold, expressing the level of uncertainty in the perceptual judgment, was, on average, 14.3 mm ($SD = 8.9$ mm). It was not affected by group, $F(2, 27) = 0.82$, $p = .45$, or by block of trials, $F(5, 135) = 0.25$, $p = .94$. Furthermore, no interaction between the two factors was observed, $F(10, 135) = 1.31$, $p = .23$. Thus, the difficulty in achieving the perceptual judgment was not dependent on the experimental conditions (see Table 1).

Correlation between motor performance and perceived reachability limit When individual performances were analyzed, radial error (according to actual target location) in the motor task was found to correlate with radial error in the reachability estimates in the shift-toward group (linear correlation coefficient was, on average, $r = -.86$, and 9 participants out of 10 showed a correlation coefficient significantly different from 0; see Table 2). In the shift-away group, linear correlation coefficient was, on average, $r = -.39$. However, as was mentioned above, the boundary of perceived reachable space shifted in an unexpected direction in the second block of trials according to the block of trials 1. When only blocks of trials 2–6 were considered, linear correlation coefficient was, on average, $r = -.70$, and 8 participants out of 10 showed a correlation coefficient significantly different from 0. No correlation between radial errors and reachability estimates was found in the no-shift group, in which no visuomotor recalibration was required (linear correlation coefficient was, on average, $r = -.29$, and only 2 participants out of 10 showed a correlation coefficient significantly different from 0).

Fig. 3 **a** Radial errors (in millimeters) and standard errors for the shift-toward (black), shift-away (gray), and no-shift (white) groups in the six blocks of trials when the perceptual judgment task was performed. The 0 value represents the actual reachability limit, positive values indicate overestimation, and negative values indicate underestimation. Concurrent effect of adaptation on motor (according to actual target distance)

Furthermore, when expressed as a Z score, correlation coefficients in the shift-toward group were not different from correlation coefficients in the shift-away group, $t(9) = 1.14$, $p = .28$, although they both differed from the no-shift group, $t(9) = 4.80$, $p < .01$, and $t(9) = 2.75$, $p = .02$, respectively. As a whole, these results showed a clear effect of the visuomotor adaptation on perceived reachable space, in the sense that any modification in the relation between visual distance and movement parameters led to a concomitant shift in the location of the perceived reachable space (see Fig. 3b–d).

Relation between response time and the boundary of perceived reachable space When fitting RT according to target location using a Gaussian regression model, we found for the no-shift group that maximum RT (1,014 ms) occurred, on

and perceptual (according to actual reachability limit) performances are shown for the no-shift (**b**), shift-toward (**c**), and shift-away (**d**) groups in the six blocks of trials. Note that any change in motor performance goes with a change of similar amplitude in the boundary of perceived reachability, except for the sixth block of trials in the shift-toward group and the second and fourth blocks in the shift-away group

average, at a distance of -4.3 mm ($SD = 44$ mm) from the actual maximum reachable distance (coefficient of determination for the Gaussian fit was, on average, $r^2 = .54$, $p < .01$). For the shift-toward group, maximum RT (1,004 ms) was found to occur, on average, at a distance of -27.5 mm ($SD = 68$ mm) from the actual maximum reachable distance (coefficient of determination for the Gaussian fit was, on average, $r^2 = .54$, $p < .01$). For the shift-away group, maximum RT (981 ms) was found to occur, on average, at a distance of 15.6 mm ($SD = 45.3$ mm) from the actual maximum reachable distance (coefficient of determination for the Gaussian fit was, on average, $r^2 = .55$, $p < .01$). The distance at which maximum RT occurred in the perceptual task was different depending on the group and the block of trials, $F(10, 135) = 5.39$, $p < .01$. In the first block of trials, the distance at which maximum RT occurred was

Table 2 Individual correlations between the radial error in the motor tasks and the location of perceived reachability limit in the perceptual task, for the shift-toward group, shift-away group, shift-away group when blocks of trials 2–6 are considered, and no-shift group

Participant	Shift Toward (Blocks 1–6)	Shift Away (Blocks 1–6)	Shift Away (Blocks 2–6)	No Shift (Blocks 1–6)
1	-.73 *	-.03	-.25	.68
2	-.89 *	.53	.31	-.58
3	-.91 *	-.23	-.91 *	-.84 *
4	-.99 *	-.06	-.92 *	-.62
5	-.96 *	-.64	-.78 *	-.47
6	-.95 *	-.79 *	-.96 *	.67
7	-.75 *	-.74 *	-.97 *	-.85 *
8	-.66	-.94 *	-.87 *	-.12
9	-.93 *	-.79 *	-.83 *	-.41
10	-.85 *	-.25	-.80 *	-.35
mean	-.86	-.39	-.70	-.29

*Significant correlation coefficient

similar whatever the group, $F(2, 27) = 0.09$, $p = .91$ (for the shift-toward group, 14.8 mm [$SD = 74$ mm]; for the shift-away group, 25.7 mm [$SD = 59.3$ mm]; for the no-shift group, 20.6 mm [$SD = 30.4$ mm]), whereas in the sixth block of trials, it was farther in the shift-away group (33.6 mm [$SD = 31.5$ mm]) and closer in the shift-toward group (-56.6 mm [$SD = 63.1$ mm]), as compared with the no-shift group (4.7 mm [$SD = 43.3$ mm]), $F(2, 27) = 9.29$, $p < .01$ (see Table 1).

The distance corresponding to the maximum RT was found to correlate with the distance of perceived boundary of reachable space across the different groups and blocks of trials, as revealed by the significant linear correlation, $r = .92$, $p < .01$. When the groups were considered separately, the linear regression coefficients were, on average, $r = .89$, $r = .92$, and $r = .91$, in the no-shift, shift-toward, and shift-away groups, respectively (all $ps < .01$).

Discussion

The aim of the present experiment was to evaluate in a visuomotor task whether adaptation to shifted visual feedback about manual reaching performance would influence the perception of reachable space. As the discrepancy between target location and corresponding motor response was progressively increased by iteratively shifting the visual feedback, a congruent variation of the boundary of perceived reachable space was expected, depending on the direction and amplitude of the feedback shift. Data showed that visuomotor adaptation to shifted visual feedback was successfully achieved in all groups and in all blocks of trials. As a consequence, reaching movements were performed with the same amplitude throughout the experiment, despite a variation of target location of up to ± 75 mm. No effect of visuomotor adaptation was observed on movement kinematics, reaction time, and movement time,

indicating that intrinsic movement parameters were kept unchanged during the whole experimental session. Furthermore, adaptation was achieved through the repetition of only a few trials when a new shift of the visual feedback was suddenly introduced. These results attest, then, that transient motor adaptation to shifted visual feedback can appear in a very short time period along the spatial dimension tested, without implying a major reorganization of the temporal and kinematic characteristics of the motor output, as demonstrated in several previous studies (Boy, Palluel, Orliaguet, & Coello, 2005; Palluel-Germain, Boy, Orliaguet, & Coello, 2004; Redding, Rossetti, & Wallace, 2005).

Interestingly, none of the participants exhibited awareness of the shifted visual feedback during the whole experiment and even during the postexperiment interview. Despite the large discrepancy between movement end point and target location in the last block of trials (± 75 mm), visuomotor adaptation remained unnoticed by the participants, due obviously to the iterative adaptations of small amplitude imposed in the successive blocks of trials (± 15 mm), implying mainly automatic processing of spatial errors and unconscious adaptive processes (Serrien & Spapé, 2011; Wong & Henriques, 2009).

Concerning the perceptual task, reachability judgments slightly overestimated actual action capabilities (23.8 mm on average, first block of trials), confirming the results obtained in previous studies (Bootsma et al., 1992; Carello et al., 1989; Coello & Iwanow, 2006; Fischer, 2000; Gabbard et al., 2006; Rochat & Wraga, 1997). In these studies, a tendency toward overestimation was reported—in particular, when estimates of reachability were provided in darkness or in the presence of postural constraints (as in the present study). However, the main result gained in the present study was that the boundary of reachable space as reported by the participants was significantly affected by the visuomotor adaptation to shifted visual feedback about manual reaching

performance. Although movement amplitude was kept constant across the experiment, while corresponding to different visual target locations, the change in the relation between movement amplitude and target distance induced by the visuomotor adaptation affected where the boundary of reachable space was perceived. In the shift-toward group, the boundary of reachable space was perceived progressively closer to the perceiver as the feedback about movement end point was iteratively approaching in space. In contrast, in the shift-away group, the boundary of reachable space was perceived progressively farther from the perceiver as the feedback about movement end point iteratively receded in space. Furthermore, we found that RT in the perceptual task varied according to the distance of the target, with peak of RT systematically occurring at a distance corresponding to the perceived boundary of reachable space, which was thus influenced by the visuomotor adaptation (see Hirose et al., 2010, for similar results with graspability judgments).

Thus, changing the visuospatial consequence of acting toward a particular target by introducing a shifted visual feedback about motor performance had a direct and predictable effect on the distance at which the boundary of reachable space was perceived. In the no-shift group, a group in which no distorted feedback was presented, no variation of the boundary of reachable space was observed. By contrast, performing manual reaching actions with the same amplitude for targets located farther away than before adaptation induced the perception of reachability for targets that were initially unreachable. Conversely, performing manual reaching actions with the same amplitude in the presence of targets located closer than before adaptation induced the perception of unreachability for targets that were initially reachable.

Surprisingly, we also noticed that the expected effect of adaptation on perceived boundary of reachable space was not present during the first period of visuomotor adaptation for the shift-away group (block of trials 2). We indeed observed that whatever the direction of the shift of the visual feedback (± 15 mm), visuomotor recalibration in the shift-away and shift-toward groups induced a variation of the boundary of reachable space in the same direction and toward a reduction of perceived reachable space. With respect to the methodology used, visuomotor recalibration was thought to occur when the previously learned correspondence between visual distance and reach amplitude was modified by introducing a shift in the visual feedback about movement end point. This recalibration was thought to be dependent on the direction of the feedback shift and, thus, to induce symmetrical variation of the boundary of perceived reachable space in the shift-away and shift-toward groups, which was not observed. A similar asymmetry has been observed by Mon-Williams and Bingham (2007), who reported that visuomotor recalibration is more efficient when leading to a reduction instead of an extension of reach

space. However, it is worth noting that in our study, the asymmetry concerned perceptual judgments with greater changes when a reduction was induced, instead of an extension of perceived reachable space, while motor responses adapted similarly in both directions. Moreover, changes of perceptual judgments in the remaining blocks of trials (i.e., after a block of trials 2) were congruent with the visuomotor recalibration, as indicated by individual correlations. The unexpected variation of the boundary of reachable space occurred, then, only in the block of trials in which the distorted feedback was introduced for the first time (block 2), and mainly for the shift-away group.

One possible interpretation for this unexpected effect could be that in addition to introducing a discrepancy between motor response and target visual location (which is thought to induce a recalibration process), shifting the visual feedback may also have resulted in a perceived increase of the variability between expected and actual visual feedback location. Although this remained unnoticed by the participants, this alteration of the movement–target correspondence may have been interpreted as an increased variability of the visuomotor system, leading to a conservative, yet unconscious, strategy affecting the visual perception of reachability (Fajen, 2005; Gabbard et al., 2006; Gabbard, Ammar, & Rodrigues, 2005). Some previous data support this interpretation by showing that increasing uncertainty in a sensorimotor task affects perceptual judgments of object properties (Ernst & Banks, 2002), as well as perceptual learning (Barthelmé & Mamassian, 2009; Shibata, Yamagishi, Ishii, & Kawato, 2009). In the present experiment, the induced discrepancy between visual and motor-related information may then have been concurrently perceived as a sudden increase of the variability of the visuomotor system, resulting in a reduction of the confidence attributed to the sensorimotor anticipatory processes (Gabbard et al., 2006; Gabbard et al., 2005). Modifying the state of confidence may have subsequently influenced the perception of reachable space, inducing a conservative strategy when reachability estimates were provided. The effect of increasing visuomotor variability on reachability estimates would, furthermore, be more expected in the first block of adaptation trials (block of trials 2), since the amplitude of the visual feedback shift remained constant afterward across the following blocks of trials (blocks of trials 3–6), thus maintaining the enhanced variability of the visuomotor system at a constant level.

To test this assumption, we designed a complementary experiment in which the visual feedback about movement end position was randomly shifted (within the interval of ± 7.5 mm), but keeping the average relation between target, feedback, and movement end point location unaffected. Our hypothesis was that if slightly increasing the variability of the visuomotor system affects the perception of reachable space, providing a randomly shifted visual feedback about movement end point should influence the location at which

the boundary of reachable space is perceived, due to the prevalence of a conservative strategy in this condition.

Experiment 2

The aim of this experiment was to evaluate whether introducing a random, although unnoticed, shift of the visual feedback about motor response accuracy would induce a reduction of perceived reachable space, despite the fact that target location, average visual feedback location, and average motor performance remained unchanged.

Method

Participants, apparatus, and procedure The present experiment involved 10 healthy participants (7 males and 3 females), with normal or corrected-to-normal vision, and ages ranged from 24 to 31 years ($M = 27.5$, $SD = 2$). They were self-declared volunteers and gave their informed consent prior to their inclusion in the experiment. They were all right-handed, as assessed by self-report from a ten-item questionnaire adapted from the Edinburgh Handedness Inventory (Oldfield, 1971; mean laterality quotient was .96, with a range from .79 to 1). The apparatus and procedure were similar to those in Experiment 1, except for the following details.

The experiment consisted in two successive blocks of 184 trials. Each block of trials consisted of a motor task (60 trials) followed by a perceptual task (124 trials). In the motor task, participants were requested to reach as quickly and accurately as possible with their right hand to the adaptation target presented at 80, 110, or 140 mm from the maximum reachable distance. Visual feedback was provided every trial during the first 24 trials, whereas during the last 24 trials, it was provided every 2 trials, on average (Bingham et al., 2007). The feedback was available for 500 ms after the target disappeared, the hand being still located at the movement end point. In the first block of trials, visual feedback actually corresponded to the movement end point, but in the second block of trials, the position of the feedback was randomly shifted by ± 7.5 mm. Thus, manual reaching movements had to be performed to the same distance in the two blocks of trials, but visual feedbacks indicated greater variability of the visuomotor performance in the second block of trials. Following the set of 48 trials in each block of trials, manual reaching movements were performed toward the two test targets used to evaluate the current visuomotor calibration (12 trials toward targets presented at 95 and 125 mm from the maximum reachable distance), with no feedback provided at movement end point.

The perceptual task was performed after each visuomotor task, and the 31 targets were presented 4 times in a random order in the two blocks of trials. The targets were presented at

distances of 110 mm up to 410 mm from the starting position used in the motor tasks. As in Experiment 1, the task for the participants was to estimate whether the target presented was reachable or not with their right hand, without having the possibility to actually move their upper limb. Data in the present experiment (random-shift group) were compared with data obtained in Experiment 1 by the no-shift group, for which the visual feedback was always provided on the actual location of movement end point (blocks of trials 1 and 2).

Statistical analyses were carried out separately for the perceptual and the motor tasks on the different variables through a two-way ANOVA (block of trials [B1, B2] $\times$ group [no shift, random shift]) with repeated measures on the first factor only. Normality of performance distribution and homoscedasticity were tested for the different groups in the first block of trials. Furthermore, in case the sphericity assumption was violated (i.e., epsilon smaller than 1), Huyn–Feldt adjustments of the p -values were reported.

Results

Mean arm length, measuring the distance between the shoulder joint (about 45 cm above the workspace) and the tip of the index finger while the arm was stretched was 67.9 cm. Thus, the average maximum reachable distance on the workspace was located at 50.5 cm from the body and at 27.5 cm from the starting position of the hand along the sagittal axis.

Motor task

Reaction time In the motor task, reaction time was, on average, 431 ms ($SD = 88$ ms). It was not affected by group, $F(1, 18) = 0.21$, $p = .65$ (for the no-shift group, 422 ms [$SD = 92$ ms]; for the random-shift group, 441 ms [$SD = 87$ ms]). Reaction time was affected by block of trials, $F(1, 18) = 6.18$, $p = .02$ (for block 1, 441 ms [$SD = 90$ ms]; for block 2, 422 ms [$SD = 88$ ms]). However, there was no interaction between the two factors, $F(1, 18) = 0.61$, $p = .45$.

Spatial performance Radial error relative to target location when the motor task was performed was -2.72 mm ($SD = 6.1$ mm), on average, and did not differ across the blocks of trials, $F(1, 18) = 0.04$, $p = .85$. Radial error was also not affected by group, $F(1, 18) = 1.86$, $p = .19$, and no interaction was observed between the two factors, $F(1, 18) = 1.14$, $p = .30$ (see Table 3 for data details). Furthermore, radial error variability was not affected by group, $F(1, 18) = 0.07$, $p = .80$, or by block of trials, $F(1, 18) = 0.01$, $p = .94$, and there was also no interaction between the two factors, $F(1, 18) = 1.43$, $p = .25$. These results show that despite the introduction of a randomly shifted feedback, average radial error and radial error variability

Table 3 Means and standard deviations in [Experiment 2](#) for the location of perceived reachability limit (Boundary), discrimination threshold (DT), and response time (RT), and for radial error (Rad. Err.), angular error (Ang. Err.), reaction time (RT), movement time (MT), peak velocity (PV), and percentage of time taken by the acceleration period (DAP) in the motor task

	Random Shift	
	Block 1	Block 2
Perceptual task		
Boundary (mm)	26.9 (23.3)	0.8 (27.9)
DT (mm)	15.3 (9.9)	12.2 (8.9)
RT (ms)	692 (100)	660 (106)
Motor task		
Rad. Err. (mm)	−0.5 (5.7)	−1.9 (7.5)
Ang. Err. (deg)	0.3 (3.4)	1.1 (2.7)
RT (ms)	453 (85)	428 (91)
MT (ms)	706 (150)	713 (128)
PV (mm/s)	408 (160)	381 (131)
DAP (%)	44 (4.3)	43.5 (6.7)

did not differ from those in [Experiment 1](#) in the condition where accurate feedback was provided.

Angular error was 0.66° ($SD=3.1^\circ$), on average, and also was not affected by block of trials, $F(1, 18) = 0.31$, $p = .58$, or by group, $F(1, 18) = 0.01$, $p = .96$. No interaction was observed between the two factors, $F(1, 18) = 1.67$, $p = .21$. Thus, hand trajectory ended consistently slightly to the left of the target in both blocks of trials for the two groups (see [Table 3](#)). Participants then performed the manual reaching movements with the same accuracy in both blocks of trials, and not differently from [Experiment 1](#), despite the increased variability in the position of the visual feedbacks in the second block of trials of the present experiment.

Temporal and kinematic parameters The duration of manual reaching movements was, on average, 719 ms ($SD = 118$ ms) and was not affected by block of trials, $F(1, 18) = 0.04$, $p = .84$, or by group, $F(1, 18) = 0.14$, $p = .71$. No interaction was observed between the two factors, $F(1, 18) = 0.06$, $p = .80$. There was also no effect of block of trials on the maximum velocity reached during hand transport (on average, 0.36 m.s^{-1} , $SD = 0.13 \text{ m.s}^{-1}$), $F(1, 18) = 1.42$, $p = .25$, no effect of group, $F(1, 18) = 1.72$, $p = .21$, and no interaction between the two factors, $F(1, 18) = 0.44$, $p = .51$. The percentage of time taken by the acceleration period was, on average, 42.5 % ($SD = 5.3$ %, and thus, 57.5 % for the deceleration period). It was not affected by block of trials, $F(1, 18) = 0.08$, $p = .78$, or by group, $F(1, 18) = 1.31$, $p = .27$, and no interaction between the two factors was observed, $F(1, 18) = 0.04$, $p = .85$. Consequently, the intrinsic characteristics of hand movements were kept unchanged across the blocks of trials and were,

thus, not affected by the feedback manipulation, since they did not differ from those observed in the no-shift group ([Experiment 1](#)), in which no feedback manipulation was used (see [Table 3](#)).

Perceptual judgment task

Response time In the perceptual judgment task, RT was, on average, 734 ms ($SD = 120$ ms). It was affected by block of trials, $F(1, 18) = 14.88$, $p < .01$, (for block 1, 764 ms, $SD = 126$ ms; for block 2, 704 ms, $SD = 108$ ms) and by group, $F(1, 18) = 7.00$, $p = .02$ (for the no-shift group, 791 ms, $SD = 110$ ms; for the random-shift group, 676 ms, $SD = 102$ ms). No interaction between the two factors was observed, $F(1, 18) = 3.16$, $p = .09$.

Boundary of perceived reachable space The boundary of reachable space was perceived, on average, at 16.0 mm ($SD = 28.6$ mm) with respect to the actual reachability capacities. The location in space of the boundary of reachable space was, however, affected by block of trials, $F(1, 18) = 18.57$, $p < .01$ (for block 1, 23.9 mm, $SD = 25.6$ mm; for block 2, 8.1 mm, $SD = 29.8$ mm), but no significant difference was observed between the two groups, $F(1, 18) = 0.13$, $p = .72$ (for the no-shift group, 18.2 mm, $SD = 29.4$ mm; for the random-shift group, 13.9 mm, $SD = 28.4$ mm). However, an interaction between group and block of trials was observed, $F(1, 18) = 7.99$, $p = .01$. Indeed, while the boundary of reachable space was not dependent on the block of trials in the no-shift group, $F(1, 9) = 2.60$, $p = .14$ (for block 1, 20.9 mm, $SD = 28.7$ mm; for block 2, 15.5 mm, $SD = 31.3$ mm), a significant reduction of perceived reachable space was observed in the random-shift group, when the visuomotor variability as provided by the terminal feedback increased, $F(1, 9) = 16.13$, $p < .01$ (for block 1, 26.9 mm, $SD = 23.3$ mm; for block 2, 0.8 mm, $SD = 27.9$ mm; see [Fig. 4](#)). These results indicate a specific effect of feedback manipulation on reachability estimates in the present experiment.

The discrimination threshold, expressing the level of uncertainty in the perceptual judgment, was, on average, 16.2 mm ($SD = 9.8$ mm). It was not affected by block of trials, $F(1, 18) = 0.01$, $p = .93$, or by group, $F(1, 18) = 18.5$, $p = .19$. Furthermore, no interaction was observed between the two factors, $F(1, 18) = 14.3$, $p = .25$. Thus, the difficulty in achieving the perceptual judgment was not dependent on the experimental condition.

Discussion

The aim of the present experiment was to evaluate in a visuomotor task whether randomly shifting the visual

Fig. 4 Radial errors (in millimeters) and standard errors for the random-shift group in [Experiment 2](#) and the no-shift group in [Experiment 1](#), considering the first two blocks of trials when the perceptual task (according to actual reachability limit) was performed. The 0 value represents the actual reachability limit, positive values indicate overestimation, and negative values indicate underestimation

feedback about motor performance would affect afterward the perception of reachable space. Considering the results as a whole, we found that slightly increasing the variability of the visuomotor system, by shifting in a nonpredictable way visual feedback about the spatial accuracy of a reaching movement, led to a reduction of perceived reachable space. In the motor task, spatial accuracy was not affected by random variation of the visual feedback, and intrinsic characteristics of the motor responses (reaction time and kinematic parameters) remained unchanged. Consequently, randomly varying visual information about motor performance induced no adaptation of the visuomotor system, and motor performance was found to be similar to that observed in the no-shift condition. Actually, hand trajectory consistently reached a position corresponding to the average location of the visual feedback close to the center of the visual target. As a consequence, a significant difference was observed between actual motor variability and visual feedback variability, $t(12) = -7.16$, $p < .01$: Visual feedback indicated more variable visuomotor performance, as compared with the actual variability. Randomly shifting the visual feedback about motor performance by ± 7.5 mm thus increased uncertainty in visuomotor processing without affecting the average motor response toward the visual targets and its variability.

However, although randomly shifting the visual feedback did not affect average motor performance, it sharply influenced perceptual estimates of reachability. The boundary of perceived reachable space was found to be located 26 mm closer to the perceiver in the presence of a randomly shifted visual feedback, as compared with the condition in which the visual feedback was accurate. This reduction of perceived

reachable space can hardly be interpreted as a mere consequence of motor practice, since the same number of motor responses was provided in both groups. The sole difference in the two groups was the presence of a random shift of visual feedback location in the random-shift group, which had proved to affect reachability estimates. In contrast, discrimination threshold was not influenced by the presence of the randomly shifted visual feedback, indicating that the perceptual decision was not more difficult to achieve in this particular condition, as compared with the condition in which visual feedback was constantly accurate. This result strongly suggests that in the present experiment, perceived reachable space was influenced primarily by the perceived reliability of the visuomotor system. Indeed, although the average motor performance remained unchanged (both in accuracy and variability, whatever the accuracy of the visual feedback), increasing the discrepancy between actual movement end point and perceived movement end point and, thus, the uncertainty in visuomotor processing led to a significant reduction of perceived reachable space. Moreover, the reduction of perceived reachable space achieved although the experimental manipulation remained unnoticed by the participants, during both the experiment and the postexperiment interview.

Interestingly, the reduction of perceived reachable space when the variability of the visual feedback (26.1 mm) was increased was found to be of about the same magnitude as the reduction of perceived reachable space observed in [Experiment 1](#) when a constant feedback shift of 15 mm was introduced for the first time (block of trials 2) in the shift-toward (37.4 mm) and shift-away (27.4 mm) groups. It is thus tempting to interpret the unexpected reduction of perceived reachable space for the two groups in this particular block of trials as resulting from a sudden increase of the visuomotor variability leading to an implicit conservative strategy in order to minimize the risk of perceptual error (Fischer, 2000; Rochat & Wraga, 1997). Because visuomotor variability remained unchanged in the following periods of adaptation of [Experiment 1](#) (block of trials 2–6), visuomotor adaptation could occur and also affect, although differently, perceived reachable space. Similarly, the greater effect of visuomotor adaptation on perceived reachable space in the shift-toward group could result from a cumulative effect of visuomotor recalibration and conservative strategy in this condition.

Conclusion

To summarize, the present study extends previous data that have shown that spatial perception can be modified by motor experience (Coello & Delevoye-Turrell, 2007; Proffitt, 2006). It also provides further evidence for the remarkable plasticity of the sensorimotor system, since the relation between the

sensory and motor systems was updated following a few movement rehearsals in the presence of the shifted visual feedback, so as to adapt to the new visuomotor constraints (Boy et al., 2005; Palluel-Germain et al., 2004; Redding et al., 2005). The observation that the visual perception of reachable space depends on both calibration and reliability of the visuomotor system represents the original findings of this study. Although the critical role of the state of confidence relating to the sensory and motor systems on perceptual decision making has already been suggested in the past (Barthelmé & Mamassian, 2009; Mamassian, 2008; Nagengast, Braun, & Wolpert, 2010), the present study revealed for the first time that it can also influence perceived reachable space. The visual perception of reachable space must, then, be viewed as depending on a motor-related perceptual system, which is affected by both visuomotor calibration and the level of confidence in the visuomotor system.

Acknowledgments This work was supported by grants from the University Lille 3, the Région Nord Pas de Calais and the ANR “Interact” programme from the French Ministry.

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