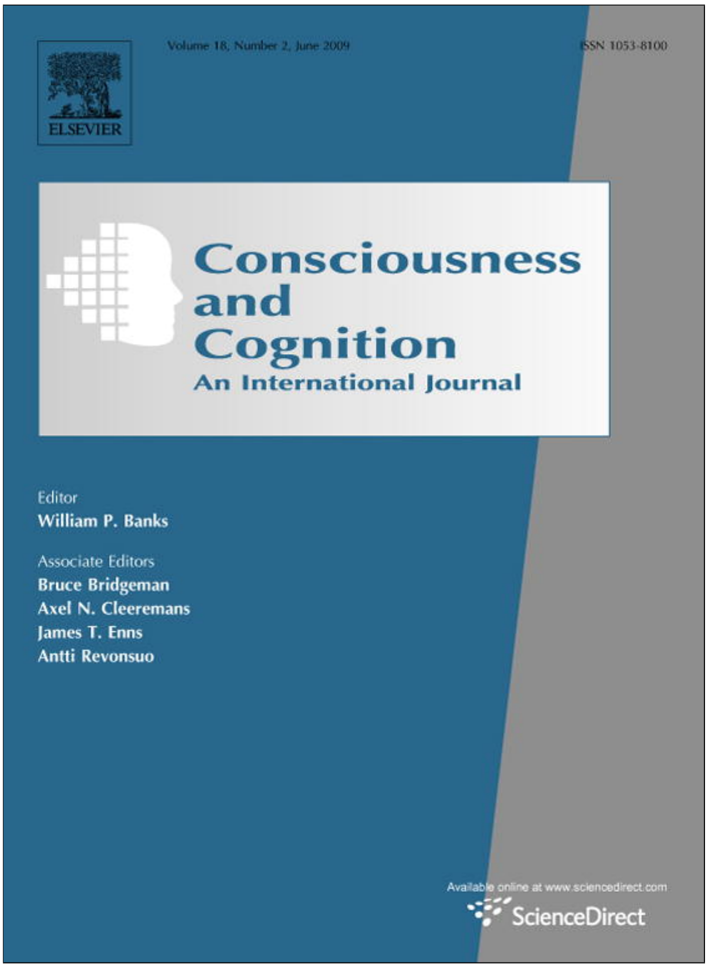
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Perceiving one's own movements when using a tool

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ABSTRACT

The present study examined what participants perceive of their hand movements when using a tool. In the experiments different gains for either the *x*-axis or the *y*-axis perturbed the relation between hand movements on a digitizer tablet and cursor movements on a display. As a consequence of the perturbation participants drew circles on the display while their covered hand movements followed either vertical or horizontal ellipses on the digitizer tablet. When asked to evaluate their hand movements, participants were extremely uncertain about their trajectories. By varying the amount of visual feedback, findings indicated that the low awareness of one's own movements originated mainly from an insufficient quality of the humans' tactile and proprioceptive system or from an insufficient spatial reconstruction of this information in memory.

1. Introduction

Intentional actions require a goal, that is, some anticipatory representation of the expected action effects. With regard to the so-called ideomotor principle the anticipations of these action effects even fulfill a generative function in motor control: actors select, initiate, and execute an intended movement by activating the anticipatory codes of the action's effects (Greenwald, 1970; James, 1890; for recent overviews and empirical evidence see, e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; Nattkemper & Ziessler, 2004).

When using a tool, humans have to deal with two, not necessarily concordant effects of their actions: on the one hand the proximal, body-related action effects, like the tactile sensation from the moving finger, and on the other hand the distal action effects, for example, the cursor on a display controlled by the user's mouse movements. As in tool use the intentional goal is usually directed to the distal effect, it should be predominant. Indeed, several studies have already shown the importance of distal action effects in tool use (e.g., Kunde, Müsseler, & Heuer, 2007; Massen & Prinz, 2008; Müsseler, Kunde, Gausepohl, & Heuer, 2008; Rieger, Knoblich, & Prinz, 2005). For instance, Mechsner and colleagues were able to demonstrate that the normally observed inferiority of asymmetrical over symmetrical cyclic hand movements disappears when asymmetric hand movements are transformed into visible and controlled symmetric tool movements (Mechsner, Kerzel, Knoblich, & Prinz, 2001). In another study by Riggio and colleagues, participants used sticks to press response keys and the sticks were crossed or uncrossed. This allowed the spatial correspondence to vary orthogonally between the imperative stimulus, the location of the hand, and the location of the intended action effect (the tip of the stick). The authors found that what counted was the spatial correspondence between the stimulus and the intended action effect (Riggio, Gawryszewski, & Umiltà, 1986). This is clear evidence that the distal action effects are able to overrule the proximal action effects in motor control.

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It is likely that the predominance of the distal action effect over the proximal action effect corresponds with their degree of awareness. To the extent, to which the distal action effect in tool use is predominant, the proximal action effect should step back. In the present paper we therefore address the question what humans perceive of their hand movements when using a tool. In accordance with the ideomotor principle humans should be mainly aware of their intended distal action effects, while the proximal action effects are largely neglected. Thus, although humans feel a high degree of motor control, when using their hands, and although hand movements are remarkably accurate, humans should be little aware of what their hands are doing when using a tool.

This assumption has been also specified in the internal model theory of motor control (Frith, Blakemore, & Wolpert, 2000; Wolpert & Kawato, 1998), which assumes two functionally different components, an inverse model and a forward model. The inverse model provides the motor commands necessary to achieve the intended action effects, while the forward model predicts the action effects of an executed motor program. The authors postulated that humans are mainly aware of the intended consequences of movements but less aware of the actual sensorial consequences.

Several studies have already provided empirical evidence for this assumption (e.g., Fourneret & Jeannerod, 1998; Knoblich & Kircher, 2004; Sülzenbrück & Heuer, 2009). For example, in the study of Fourneret and Jeannerod (1998) participants traced sagittally a straight line by moving a stylus on a digitizer tablet. In some trials, angular perturbations ($-10°$ to $+10°$ to the left or right) were introduced between the actual hand movement and its visual consequences on the screen. In perturbed trials participants grossly underestimated their hand deviations. However, this finding was accompanied by contradictory judgments of the participants: a post-hoc analysis revealed that one group of participants misperceived the direction of their hand movements in the direction opposite to the perturbation, while the other group gave responses in the correct direction.

In a study by Knoblich and Kircher (2004; see also Sülzenbrück & Heuer, 2009) participants carried out a circle-drawing task on a digitizer tablet in which the relative velocity between the actual movement and its visual consequences was perturbed at a point in time of the movement. The participants' task was to detect these changes in the relative velocity of the hand movements and their visual consequences on the display by lifting the stylus from the digitizer tablet. Results revealed again that the threshold for conscious detection of the discrepancies is relatively high. It seems that the conscious system is deceived about the amount of control it exerts. Other studies were also eager to demonstrate that conscious change detection relies on a system that integrates information from the (proximal) motor system with the (distal) visual system (e.g., Franck et al., 2001; Leube, Knoblich, Erb, & Kircher, 2003). However, if the participants' task is to detect changes between the hand movement and its distal consequences, a cognitive process comparing both sources of information is very likely (cf. Frith et al., 2000; Jeannerod, 2003).

Therefore, the aim of the present study was twofold: firstly, it aimed to explore what participants perceive of their hand movements when the detection task is omitted from the procedure. In other words, participants' task was not to detect discrepancies between hand movement and distal movements' effect, but they were asked to evaluate their hand movements in a task, which is addressable by referring to the proximal hand movements alone. The basic experimental set-up is illustrated in Fig. 1. The participants sat in front of a digitizer tablet and tracked a circular moving target on a display in front of them. By experimentally manipulating either the gain for the *x*-axis or the *y*-axis between digitizer tablet and display, the correspond-

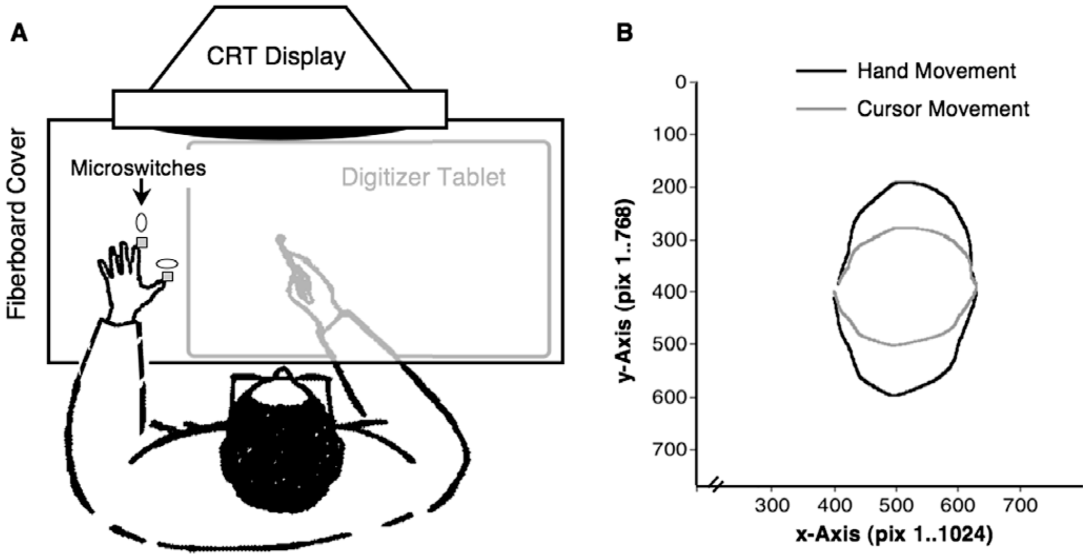

Fig. 1. (A) The set-up in the experiments. The participants sat in front of a digitizer tablet with the stylus in their right hand. Hand, stylus and digitizer tablet were covered by a fiberboard and participants indicated with their left hand by pressing one of two microswitches, whether their hand movement had performed a vertical or horizontal ellipse. (B) Typical *xy*-trajectories of the proximal hand movement (black line) and the distal cursor movement on the display (grey line). Participants always produced circle trajectories on the display, but the corresponding hand movement was either a vertical or horizontal ellipse (here a vertical ellipse).

ing hand movement had to produce either a vertical or a horizontal ellipse in order to follow the circle on the display. In Experiments 1 and 2c the question of interest was to which extent participants were able to evaluate correctly their hand movements with these conditions.

Secondly, the study aimed to compare what do participants perceive of their hand movements when the distal consequences of their hand movements (i.e. the cursor movements on the display) were presented or not. A comparison between both conditions in Experiments 2a and 2b revealed information about the impact of the distal action effects on the perception of the proximal hand movements.

2. Experiment 1

Experiment 1 determined the thresholds of what participants perceive of their hand movements in a tracking task with a sensorimotor transformation (Fig. 1). An adaptive staircase procedure (Cornsweet, 1962; von Békésy, 1947) with the following two key features was applied: firstly, the gain size for the *x*-axis or the *y*-axis was adapted individually to the participants' performance determining iteratively the threshold values for the staircase of the horizontal ellipses and for the staircase of the vertical ellipses (see below). Secondly, the two staircases were randomly presented affecting either the *x*-axis or the *y*-axis. This feature is known to increase the robustness of the procedure against response tendencies, as participants were completely unaware at the beginning of each trial, which axis was perturbed and whether they had to move their hand on a vertical or horizontal trajectory.

It is worth to stress that the participants' evaluation task indicating whether they had performed a vertical or horizontal ellipse, did not require a comparison between proximal and distal movement effects, instead it referred to the proximal movement alone. The distal circles on the display were always the same and less helpful evaluating whether the performed hand movement had been a vertical or horizontal ellipse. The present experiment examined whether this task revealed similar poor results in judging one's own hand movement than the task aiming at detecting changes between proximal and distal action effects (e.g., Knoblich & Kircher, 2004).

2.1. Method

2.1.1. Apparatus and stimuli

The experiments were carried out in a dimly lit and soundproof chamber and were controlled by an Apple Macintosh computer with Matlab software using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997). The target (a black dot with a diameter of 2 mm [0.2° of visual angle]) and the cursor (a green dot with a diameter of 3 mm [0.3°]) were presented on a 22 in color CRT display (Iiyama MA203DT, 100 Hz refresh rate, 1024 × 768 pix). The target moved with a constant velocity on a grey circular pathway always visible on the display. The circle had a diameter of 78 mm (8.9°), targets' movement time to complete a full circle from the 9:00 o'clock position was 7.5 s (clockwise movement). Neither the target nor the cursor left a trace on the display. Participants were seated in front of the monitor at a distance of approximately 50 cm.

A DIN-A3 digitizer tablet (Wacom Intuos2) was placed between the display and the participant. The sample rate of the digitizer tablet was synchronized with the display rate (100 Hz). Stylus movements on the digitizer tablet and cursor movements were equally sized and the temporal delay between the movement of the stylus and the movement of the cursor on the monitor was only one refresh rate (10 ms). Hand, stylus and digitizer tablet were covered by a fiberboard and a curtain, which prevented participants from seeing their drawings with the right hand. Participants' left hand rested on the fiberboard cover with two microswitches, with which the participants indicated whether their stylus movement had formed a vertical or horizontal ellipse.

2.1.2. Procedure

The thresholds were measured with an adaptive staircase procedure and were determined in ten experimental blocks. The first block was used as a warming-up block and did not enter the data analysis. In each block two independent staircases were presented with different 1:*x* or 1:*y* gains (1:3, 1:2.4, 1:2, 1:1.72, 1:1.5, 1:1.33, 1:1.2, 1:1.09, and 1:1). In other words, either the *x*-axis or the *y*-axis was perturbed by the multiplicative factor 0.333, 0.417, 0.500, 0.583, 0.667, 0.750, 0.833, 0.917, or 1.000 yielding in horizontal or vertical ellipses of the hand movements when drawing circles on the display. Note that the step sizes of the staircases were equidistant when considering the multiplicative factors (step size of 0.083).

A trial started with three beeps (1500 Hz for 50 ms) with an interstimulus interval of 1 s. Then the target began to move and the participants' task was to track the target with the cursor. They were also informed to concentrate on their hand movements in order to identify them as vertical or horizontal ellipses at the end of a trial after performing one circle.

At the beginning of each block the two extreme 1:*x* and 1:*y* gains (each with 1:3) were realized. If at the end of a trial the participants identified their hand movement correctly as a vertical or horizontal ellipse (indicated by pressing one of the two microswitches with the participants' left hand), the next trial of the corresponding staircase was presented with a less extreme gain and so on. Then, at some point, incorrect responses occurred which indicated that participants were apparently uncertain regarding their movement trajectory. This defines a reversal point and the more extreme gain was chosen again in the next trial establishing iteratively the threshold value for each of the two staircases (the staircase of the horizontal and vertical ellipse). In case, the staircase reached the 1:1 ratio (no gain), participants' response counted as incorrect response and the more extreme gain of the staircase was chosen in the next trial. However, this was necessary in only 17 trials (0.8%) of the experiment.

A block was determined by the program when in each staircase three reversal points had occurred. After a short break a new block started again with the two extreme gains in the subsequent trial. Across the ten experimental blocks the mean number of trials performed by each participant was 217 trials (SD = 41.6).

The experimenter fed back a written error message at the end of a trial ("Spatial/temporal error of your drawing" together with a 150-ms tone of 800 Hz), when the trajectory of the cursor deviated spatially from the target trajectory by more than 20 mm or when the final position of the cursor lagged more than 1 s behind the target. In this case the trial was repeated with the same gain. The whole experiment lasted about 90 min inclusively short breaks between blocks.

2.1.3. Participants

Ten adults participated in the experiment (four female, between 19 and 37 years of age, mean age 26.2 years). In the present and the subsequent experiment, all participants reported to be right-handed and to have normal or corrected-to-normal vision.

2.2. Results and discussion

The mean reversal points of the vertical and horizontal staircases are shown in Fig. 2 (most left bars). They indicate the thresholds at which participants were unable to identify correctly whether their hands had drawn a trajectory of a vertical or horizontal ellipse. The mean gain of reversal points was 1:1.589 ($SE = 0.082$) for the vertical ellipses, while it was 1:1.590 ($SE = 0.068$) for the horizontal ellipses. Both means did not differ ($t < 1$, n.s.), but were significantly different from the 1:1 gain [$t(9) = 7.19$ and $t(9) = 8.68$, both $p < .001$].

The results showed that participants were extremely uncertain about their hand movements. The observed mean value of 1:1.59 is in the range observed by Knoblich and Kircher (2004; Experiment 1, 1:1.47 estimated from their Fig. 2), who also required participants to draw circles, but in their study the task was to detect changes between hand movements and cursor movements. Thus, we can conclude that the present evaluation task, which can be addressed by referring to the proximal hand movements alone, revealed similar poor results in evaluating one's own hand movement than the task aiming at detecting changes in sensorimotor transformation.

Possible reasons for the high threshold values were addressed in the subsequent experiments. In Experiments 2a and 2b the distal cursor movements were presented or not to examine whether the circular cursor movement had garbled the proximal hand movement. Experiment 2c checked whether the present tracking task attracted too much attention from the moving hand and therefore gave rise to the high thresholds.

3. Experiments 2a–2c

The experiment examined possible reasons for the poor ability to evaluate correctly one's own hand movement. It consisted of three parts. In Experiment 2a with a constant 1:1 gain, participants were asked to draw circles or horizontal and vertical ellipses on the display. The ellipses should deviate only in a just-noticeable way from the circles (just-noticeable ellipses, JNE). The results of the experiment allowed us to control the participants' intentions when drawing circles and just-noticeable ellipses and gave us an idea what participants perceived as just-noticeable prototypical ellipses.

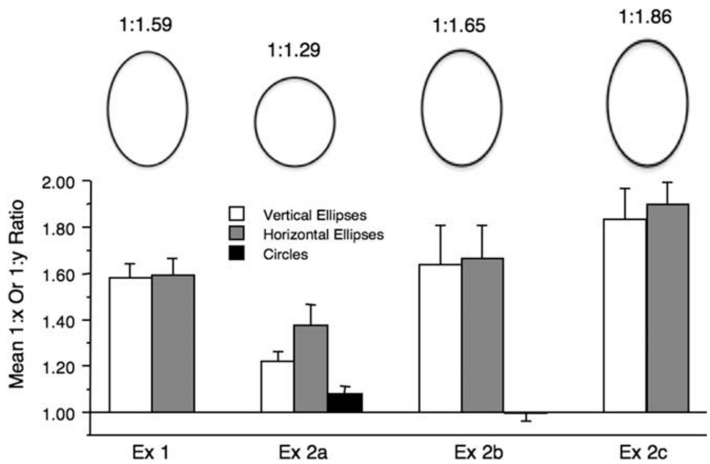

Fig. 2. Mean observed 1:*x* or 1:*y* ratios (and standard errors between participants) for vertical and horizontal ellipses in the hand movements. The bars of Experiment 1 (tracking task) and 2c (drawing task) indicated the thresholds at which participants were unable to indicate correctly whether their hand movements had performed the trajectory of a vertical or horizontal ellipse. In Experiment 2a and 2b bars indicated the 1:*x* or 1:*y* ratios of the just-noticeable ellipses, which participants had produced with (Experiment 2a) and without visual feedback (Experiment 2b). The ellipses above the bars illustrate graphically the corresponding mean ratios of the ellipses.

Experiment 2b was as Experiment 2a, but participants moved now the stylus without a distal action effect, that is without the cursor movement on the display. Again they were asked to draw circles or just-noticeable horizontal and vertical ellipses, but they did that by relying on their tactile and proprioceptive system alone. Worse performance than in Experiment 2a would indicate that the quality of the tactile and proprioceptive system is insufficient to evaluate one's own movements correctly.

Finally, in Experiment 2c the tracking task of Experiment 1 was replaced by a drawing task to examine whether the tracking task attracted too much attention from the moving hand and thereby caused the high uncertainty with which participants had evaluated their hand movements.

3.1. Method

3.1.1. Apparatus, stimuli and procedure

These were the same as in Experiment 1, except for the following changes.

In Experiment 2a, the gain was fixed to the 1:1 ratio and the grey circular pathway, always visible in Experiment 1, was deleted from the display. The experiment was run in 15 blocks with four trials each. The first two blocks were training blocks and were not analyzed. To standardize movement speed and circle size, each block started with a circular movement of the black target and, after one cycle, participants were asked to continue the movement with their green cursor for another cycle with the same speed. Only the subsequent three experimental trials entered the data analysis: participants were asked to draw circles of the same size and with the same speed just performed; or they were asked to draw just-noticeable horizontal or vertical ellipses. The corresponding instruction emphasized that participants should not just draw horizontal or vertical ellipses, rather ellipses, which deviated in a just-noticeable way from a circle. Whether the participants should draw a circle, a vertical ellipse, or a horizontal ellipse was indicated by a small icon presented in a randomized sequence at the beginning of a trial.

Experiment 2b was as Experiment 2a except that the cursor was now deleted from the display in the experimental trials. In other words, the first trial of each block was run with visual feedback on the display to standardize movement speed and circle size. Then participants were asked to draw circles and just-noticeable ellipses on the digitizer tablet without any visual feedback. Participants' hand movements of Experiments 2a and 2b were analyzed by determining the ratio of *x*-length to *y*-length of the circles and just-noticeable ellipses.

Experiment 2c was as Experiment 1, that is the staircase procedure was applied again, but the tracking task was replaced by a drawing task. To standardize movement speed, here a trial started also with a circular movement of the black target and, after one cycle, participants were asked to continue the movement with their green cursor for another cycle with the same speed. The experiment consisted of seven blocks of the staircase procedure already applied in Experiment 1. The first block served as a training block and was not analyzed.

3.1.2. Participants

Ten fresh adults (7 female, between 16 and 44 years of age, mean age 26.9 years) participated in Experiments 2a–2c. Participants run the experiments in a randomized sequence at three different days.

3.2. Results and discussion

Two main findings were observed (cf. Fig. 2): firstly, drawing just-noticeable ellipses revealed better performance with visual feedback (Experiment 2a) than without visual feedback (Experiment 2b). Correspondingly, a 2 (vertical *vs.* horizontal ellipses) $\times$ 2 (with [Experiment 2a] *vs.* without visual feedback [Experiment 2b]) within-participant ANOVA showed a significant main effect between Experiment 2a and 2b [$F(1,9) = 5.60$, $MSE = 0.23$, $p = .042$]. We can conclude that movements' tactile and proprioceptive feedback is poor to evaluate correctly the trajectories. Note, however, that in both conditions participants were quite good in drawing circles yielding in a significant interaction between factors when circles were included in the ANOVA [$F(1,9) = 6.49$, $MSE = 0.06$, $p = .008$]. Obviously, there is a high degree of uncertainty in participants' movements, when circles were transformed in just-noticeable ellipses.

Secondly, participants were also worse identifying their own hand movements with the drawing task of Experiment 2c. The mean thresholds of the staircase procedure were even higher compared to the tracking task of Experiment 1 (1:1.86 *vs.* 1:1.59; cf. Fig. 2, most left and right bars). Although an analysis of variance (ANOVA) between experiments with a 2 (vertical *vs.* horizontal ellipses) $\times$ 2 (tracking task [Experiment 1] *vs.* drawing task [Experiment 2a]) design revealed only a tendency for a corresponding main effect [$F(1,18) = 3.46$, $MSE = 0.22$, $p = .079$], we can conclude that it was surely not the more demanding tracking task which caused the high uncertainty in evaluating one's own hand movement in Experiment 1. On the contrary, as the thresholds were tendentiously lower in the tracking task than in the drawing task, the drawing task might be more demanding, but this conclusion needs certainly further experimentation.

4. General discussion

The present study aimed to evaluate what participants perceive of their hand movements when using a tool. In Experiments 1 and 2c a staircase procedure was applied and different gains for the *x*-axis and *y*-axis perturbed the relation between hand movements on a digitizer tablet and cursor movements on a display. When with these conditions participants were asked to draw circles on a display, they were extremely uncertain about their hand trajectories. Contrary to other studies the present evaluation task did not require detecting changes between proximal and distal movement effects (e.g., Knoblich & Kircher, 2004), instead it could be solved by referring to the proximal movement alone. Nevertheless, the thresholds observed in Experiments 1 and 2c were in the range of the observed thresholds in the previous study.

Two points let us believe that the observed uncertainty is still even underestimated than overestimated: firstly, in tasks with sensorimotor transformation participants are typically not asked to focus on their hand movements, but this was necessary to fulfill the present task, namely to evaluate the spatial trajectory of one's own movement. Secondly, the movement required a new on-line sensorimotor adaptation within each trial, but tool use is usually performed with a constant (or at least predictable) gain under long-term conditions. It is long known from prism experiments that perceived discrepancies between the visual position of one's own hand and its propriozeptive position disappear under conditions of long-term sensorimotor adaptation (e.g., Kohler, 1962). Both points let us believe that participants usually move their tool-using hand with an even higher degree of unawareness. When using a tool, humans do not attend their hands, but the intended effects at the tip of a tool, and they are typically long-term tool users. In this vein it is no surprise that many people are even unaware of sensorimotor transformations, which are on hand – for instance – between computer mouse and cursor movement.

Another important finding of the present study is that the unawareness of one's own hand movements was not restricted to tasks with sensorimotor transformations. When participants were asked to draw just-noticeable horizontal or vertical ellipses, participants' performance was only improved in trials with visual feedback (Experiment 2a), but was worse in trials without visual feedback (Experiment 2b). Obviously, the observed unawareness of one's own hand movements did not originate from comparing proximal with distal action effects or from integrating visual with motor information (e.g., Fourneret & Jeannerod, 1998; Frith et al., 2000; Jeannerod, 2003; Knoblich & Kircher, 2004). Instead, it mainly seemed to originate from an insufficient quality of the humans' tactile and proprioceptive system or, at least, from an insufficient spatial reconstruction of this information in memory. Since participants' task was to judge their movement trajectories at the end of each trial, it is possible that only the final reconstruction of the trajectory failed with otherwise precise position information from the tactile and proprioceptive system. On the other hand, the more direct detection task of Knoblich and Kircher (2004), which yielded grossly similar thresholds, favors the assumption of an insufficient quality of the humans' tactile and proprioceptive position system.

However, it is likely that the reason, why humans are that little aware of their hand movements, varies with the task at hand. When the task is to detect *temporal* perturbations (e.g., Franck et al., 2001; Leube et al., 2003), other stages of processing might be involved. As in this case the task is also to detect discrepancies between the actual hand position and distal positions, a processing stage comparing or integrating both sources of information might be more critical (cf. Frith et al., 2000; Jeannerod, 2003).

At a first glance, the observed low awareness of one's own actions seems to be a handicap for the human processor. It is further worth to note that tool use is not the only instance in which humans are less aware of certain aspects of their movements. For example, humans are largely unaware of the grip size when grasping at objects or of a velocity change when they conduct a goal directed movement. Another example is the poor sensing of the eye position in the absence of visual targets (for further examples see Jeannerod, 2006, chap. 3).

At a second glance, however, the unawareness of one's own actions appears to be a pre-condition for using tools successfully: especially in tool use, proximal and distal action effects are often in conflict which would result in interference, if they would be equally ranked within the system. Obviously the solution of the system is to favor the intended distal action effects while the proximal action effects step to the background. As another consequence, the low awareness of one's own actions allows for a much wider range of flexible sensorimotor adaptations and – maybe most important – they give us the feeling of control. Thus, the low awareness of one's own actions (or at least of certain aspects of one's own actions – here the evaluation of the movements' trajectory) is advantageous for using tools successfully!

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