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Costs and benefits of tool-use on the perception of reachable space

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Previous studies have shown that using a tool modifies in a short time-scale both near-body space perception and arm-length representation in the body schema. However, to date no research has specifically investigated the effect of tool-use on an action-related perceptual task. We report here a study assessing the effect of tool-use on the perception of reachable space for perceptual estimates made in reference to either the tool or the hand. Using the tool on distal objects resulted in an extension of perceived reachable space with the tool and reduced the variability of reachability estimates. Tool use also extended perceived reachable space with the hand, but with a concomitant increase of the variability of reachability estimates. These findings suggest that tool incorporation into the represented arm following tool-use improves the anticipation of action possibilities with the tool, while hand representation becomes less accurate.

1. Introduction

Perceptually determining what is reachable with the hand is critical since reachable space contains the objects with which one can immediately interact, specifies our private area in social interactions and contains the obstacles to which the organism must pay attention to in order to avoid colliding with them when gesturing or moving the body in space (for a review, see Delevoye-Turrell, Bartolo, & Coello, 2010). In the past, several studies have shown that people are quite accurate in visually specifying their reachable space (e.g., Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Coello & Iwanow, 2006; Fischer, 2000; Gabbard, Ammar, & Lee, 2006), though reachable estimates have been found to be widely influenced by the environmental context (Coello & Iwanow, 2006), the emotional states (Kennedy, Gläscher, Tyszka, & Adolphs, 2009), the postural constraints (Gabbard et al., 2006), or even the presence of mental and neurological illness (Delevoye-Turrell, Vienne, & Coello, 2011). As reachable space is structured by action, it has been proposed that the perceptual selection of reachable objects requires a motor-based perceptual system combining visual with motor- and body-related variables (Coello & Delevoye-Turrell, 2007; Holmes & Spence, 2004; Witt & Proffitt, 2008). In agreement with this, it was found that reachable objects trigger specific brain activations in motor areas (Culham & Valyear, 2006) and that artificially increasing the visual extent of a reaching movement affects the perceived size of reachable space (Bourgeois & Coello, 2012). Considered as a whole, these data support the view that the neural mechanism subtending the perception of reachable space is based on anticipating the sensory consequence of acting in the environment (Fajen, 2005; Coello & Delevoye-Turrell, 2007; Witt & Proffitt, 2008).

Non laboratory, daily living activities can also have an effect on how we perceive our reachable space. When using a tool for instance, action possibilities in the environment increase and objects unreachable with the hand become suddenly reachable. Tool-use effects on perception have been reported in neuropsychological (Farnè & Làdavas, 2000; Farnè, Iriki, & Làdavas, 2005) and behavioral (Cardinali et al., 2012; Costantini, Ambrosini, Sinigaglia, & Gallese, 2011; Witt & Proffitt, 2008; Witt, Proffitt, & Epstein, 2005) studies. Using a tool also affects how one perceives peripersonal space, as suggested by cross-modal congruency tasks (Maravita, Spence, Kennett, & Driver, 2002; Holmes, 2012; Holmes & Spence, 2004), distance matching tasks (Costantini et al., 2011; Witt & Proffitt, 2008; Witt et al., 2005), verbal distance estimates (Witt et al., 2005), and modifications of single-cell activity in the intraparietal cortex (Iriki, Tanaka, & Iwamura, 1996). When using a tool, it is thought to be incorporated into the representation of the limb within the body schema, viewed as the sensorimotor representation of the body and body segments in terms of size and position. For instance, manipulating a grabber for a few minutes was found to extend the

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sensorimotor representation of arm-length (Cardinali et al., 2011). This effect can even last for a short period following tool-use (Cardinali et al., 2012).

Previous perceptual paradigms, however, have provided only indirect measures of the effect of tool-use on the perception of what is reachable. As reported by Holmes (2012), in cross-modal congruency tasks visual stimuli were mostly located at the tool-tip and the observed effects could thus reflect changes in the allocation of visuospatial attention when manipulating tools. It remains thus unclear whether the longer represented arm-length may also impact perceptual judgments that are intimately based on the action system. Here we investigated the effect of manipulating a tool on reachability estimates, which depend on how potential actions are represented and are not restricted to verbal or relative judgments of distances like in perceptual matching task (Bingham & Pagano, 1998). Moreover, perceptual reachability judgments provide direct and finer-grained measures of the precision of the transition from reachable to unreachable space, since the different stimuli are presented at various distances from close to far locations (Bourgeois & Coello, 2012; Carello et al., 1989; Rochat & Wraga, 1997).

We reasoned that if tool-use elongates arm-length representation, reachability estimates, which are thought to depend on the represented arm within the body-schema, should be systematically altered. First, the boundary of reachable space should recede in space after tool-use when expressed in relation to the tool-tip, but also when expressed in relation to the hand. In this study, we also wanted to assess if merely holding the tool could increase perceived reachability, as suggested by some authors (Osiurak, Morgado, & Palluel-Germain, 2012; Witt & Proffitt, 2008; Witt et al., 2005). Furthermore, because using a tool contributes to the calibration of new possibilities of action in relation to the tool, we expected the precision of reachability estimates to increase when provided relative to the tool, but to decrease when provided relative to the hand due to the incorporation phenomenon. Critically, these effects are expected selectively for tools that provide a functional extension of action capabilities, but not for hand-sized tools that we introduced as controls.

2. Methods

2.1. Participants

Eighty healthy participants (all right-handed, mean age: 24.7 years, sd: 4.7 years) volunteered to participate in the study, which was performed in accordance with the local ethical committee guidelines and with the principles of the Helsinki declaration. They were randomly assigned to one of eight groups (N = 10, see below).

2.2. Stimuli and apparatus

51 visual targets (green dots, 20 mm in diameter) were randomly displayed on a horizontal screen (2 × 1.5 m) using a video-projector (Hitachi LCD projector). The screen was placed above a (80 cm × 120 cm) mirror, which projected a virtual image of the visual target on the lower part of the apparatus. The visual targets, ranging from 15 cm to 85 cm away from the participant's actual maximum reachability, were presented 4 times each, for a total of 204 stimuli per session per participant. Wooden rakes of either 10 cm or 70 cm long, providing a functional extension of arm length of respectively 0 cm and 60 cm, served as tools.

2.3. Procedure

Participants were engaged in a two-alternative forced choice (2AFC) reachability judgment task, before and after having used the 70 cm or the control 10 cm long wooden-rake, across groups. Prior to the first reachability judgment session, participants were allowed to hold the tool that they were going to use in the tool-use task, but could not manipulate it. Following the first reachability judgment session, the manipulation of the tool consisted in performing 50 reach-and-retrieve movements towards singly presented tokens (diameter: 39 mm), randomly positioned by the experimenter at different azimuthal and radial locations in order to cover the whole participant's action space, relative to either the long (70 cm) or short tool (10 cm). The effective arm extension offered by the tools (i.e., total tool-length minus handle) was 60 cm for the long rake and 0 cm for the short rake.

Depending on the experimental group, participants had to judge the reachability of the visual targets in reference to their right hand or the tip of the tool. Each visual target was displayed until response was provided by the participant, and the next trial started following a blank period of 1 s. Furthermore, the tool could be held or not while performing the reachability judgment task, which was performed both before (pre-test) and after having used the tool (post-test). To sum up, three between-participant variables were used in this experiment: “Judgment reference” (hand, tool), “Tool length” (short, long), “Tool held” (yes, no); and one within-participant variable: “Session” (pre-test, post-test).

2.4. Data recording and analysis

Reachability estimates were provided by pressing with the left hand one of two pre-defined computer keyboard keys and were recorded for off-line analysis. Perceived boundary of reachable space and response variability were determined using a logistic regression model that best fitted the reachable/unreachable responses (see Bourgeois & Coello, 2012 for details). The reachability boundary of each participant was expressed in terms of overestimation (positive values) or underestimation (negative values) as compared with the actual maximum reaching possibilities with the hand or with the tool. The variability of reachability estimates was assessed through the discrimination thresholds, defined as the difference between the distance judged as reachable 50% of the time (reachability boundary) and the distance judged as reachable 84% of the time on the regression function (Ernst & Banks, 2002). Following this calculation, the smaller the threshold values, the more accurate the separation between reachable and unreachable stimuli and, in turn, the sharper the perceived boundary of reachable space (see Fig. 1B).

Statistical analyses were carried out on the different variables through a four-way analysis of variance (ANOVA) with “Judgment reference” (hand, tool), “Tool length” (short, long) and “Tool held” (yes, no) as between-group factors, and “Session” (pre-test, post-test) as within-subject factor, and with the perceived boundary of reachable space and variability of reachability estimates as the dependent variable.

3. Results

Data analysis showed no significant effect of the “Tool held” factor, neither in the reachability estimates nor in the discrimination thresholds (all $p > .05$). This variable was thus removed from the following ANOVAs.

3.1. Reachability estimates

Overall participants overestimated reachable space although less before (pre-test: 5.3 cm, sd: 10.8 cm) than after (post-test: 8.9 cm, sd: 7.9 cm) having used the tool as shown by the significant effect of Session ($F(1,76) = 23.13$, $p < .001$, see Fig. 2A). Overestimation of reachable space was more pronounced when estimates were provided in reference to the hand (9.7 cm, sd: 7.1 cm) rather than the tool (4.5 cm, sd: 11.1 cm) as shown by the significant effect of Judgment reference $F(1,76) = 10.8$, $p < .01$. Overestimation of reachable space was also more pronounced when participants used the short tool (9.8 cm, sd: 5.7 cm) instead of the long tool (4.4 cm, sd: 11.7 cm), as shown by the significant effect of Tool length ($F(1,76) = 11.84$, $p < .001$). Significant interactions were however found between Session and Tool length