Cognition 149 (2016) 1–5

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Short Communication

The rules of tool incorporation: Tool morpho-functional & sensori-motor constraints

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ARTICLE INFO

Article history:
Received 22 January 2015
Revised 16 December 2015
Accepted 2 January 2016
Available online 7 January 2016

Keywords:
Tool-use
Body schema
Kinematics
Plasticity

ABSTRACT

Previous studies showed that using tools modifies the agent's body and space representation. However, it is still not clear which rules govern those remapping processes. Here, we studied the differential role played by the morpho-functional characteristics of a tool and the sensori-motor constraints that a tool imposes on the hand.

To do so, we asked a group of participants to reach and grasp an object using, in different conditions, two different tools: Pliers, to be acted upon by the index and thumb fingertips, and Sticks, taped to the same two digits. The two tools were equivalent in terms of morpho-functional characteristics, providing index finger and thumb with the same amount of elongation. Crucially, however, they imposed different sensori-motor constraints on the acting fingers. We measured and compared the kinematic profile of free-hand movements performed before and after the use of both devices. As predicted on the basis of their equivalent morpho-functional characteristics, both tools induced similar changes in the fingers (but not the arm) kinematics compatible with the hand being represented as bigger. Furthermore, the different sensori-motor constraints imposed by Pliers and Sticks over the hand, induced differential updates of the hand representation. In particular, the Sticks selectively affected the kinematics of the two fingers they were taped on, whereas Pliers had a more global effect, affecting the kinematics of hand movements not performed during the use of the tool. These results suggest that tool-use induces a rapid update of the hand representation in the brain, not only on the basis of the morpho-functional characteristics of the tool, but also depending on the specific sensori-motor constraints imposed by the tool.

1. Introduction

In daily life, efficient interaction with the environment requires use of a variety of tools for different functions. Several theories (Arbib, Bonaiuto, Jacobs, & Frey, 2009; Canzoneri et al., 2013; Cardinali, Brozzoli, & Farnè, 2009; Johnson-Frey, 2003) have proposed that efficient tool use relies on the incorporation of the tool itself into the so called body schema, which allows the brain to control it as accurately as a body-part (Cardinali, Frassinetti, et al., 2009; Müsseler & Sutter, 2009; van der Steen & Bongers, 2011). Increasing amounts of evidence, from neuropsychological (Berti & Frassinetti, 2000; Costantini et al., 2014; Farnè & Làdavas, 2000; Maravita, Clarke, Husain, & Driver, 2002) and behavioral studies in healthy participants (Bourgeois, Farnè, & Coello, 2014; Costantini, Ambrosini, Sinigaglia, & Gallese, 2011; Witt, Kemmerer, Linkenauger, & Culham, 2010) support such theories. It has indeed been shown that using a tool modifies the representations of both the body and the space around the body. In particular, researchers focused on the effect of using a tool that extends the reach (such as canes, sticks, rakes or golf clubs) on the representation of the space immediately around the hand, i.e. peripersonal space (see de Vignemont & Iannetti, 2014 for a review). They suggested that peripersonal space can expand to incorporate the functional extremity of the tool (Holmes, 2012; Holmes & Spence, 2004; Maravita, Spence, Kennett, & Driver,

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http://dx.doi.org/10.1016/j.cognition.2016.01.001
0010-0277/

2002; Rossetti, Romano, Bolognini, & Maravita, 2015). However, alternative interpretations have also been advanced (see Holmes, 2012 for a review on the topic) and studies have shown that peripersonal space can be modified even without using tools (Brozzoli, Cardinali, Pavani, & Farnè, 2010; Brozzoli, Pavani, Urquizar, Cardinali, & Farnè, 2009; Serino, Canzoneri, Marzolla, Di Pellegrino, & Magosso, 2015). Instead of peripersonal space, here we focus on the tool-dependent changes on body representations and in particular the body schema, which contains the morpho-functional information necessary to plan and execute movements. Crucially, what is common to all body-related tool-use studies is that for sensory and motor changes to happen, participants have to actively use, or even merely imagining to use, the tool (Baccarini et al., 2014), whereas passively holding the same tool is not sufficient (Kao & Goodale, 2009; Maravita, Spence, et al., 2002). Yet, our knowledge of the rules governing tool incorporation remains poor. In particular, it is unclear what are the specific aspects of a tool that are incorporated during tool use: its morphological-dependent function, or the specific movements required to control it?

Answering this question would be an obvious but mandatory step for developing appropriate theoretical and computational models of the sensorimotor plasticity induced by tool-use. However, very few attempts have been pursued so far in this direction. Some previous studies showed that tool induced changes are specific for the body-part (arm vs. hand) which morphology is modified by the tool. For example, an earlier study by our group found that when participants use a tool that consists in a long shaft-mounted grabber, hence mainly lengthening arm reaching possibilities, their arm -but not their hand- representation was modified. This was supported by the finding that changes in the kinematic parameters of free-hand reach-to-grasp movements performed after tool-use were solely observed in relation to the arm (i.e., on the transport component), whereas the kinematics of the fingers (i.e., the grip component), remained unaltered. Convergent support to this interpretation comes from an implicit arm length estimation task, whereby participants judged their arm, but not their hand, as being longer after the use of such tool (Cardinali, Frassinetti, et al., 2009; Cardinali et al., 2011; Sposito, Bolognini, Vallar, & Maravita, 2012). More recently, Miller and collaborators (Miller, Longo, & Saygin, 2014) reported complementary findings by testing participants in a two-point tactile distance task, before and after the use of either a tool that mainly modified the hand size, or the arm length. In other words, depending on the tool, participants could retrieve an object either by acting with a bigger hand, or a bigger arm. They found that both tools induced changes to the representation of the specific body-part whose morphology they modified, e.g., the hand –but not the arm- representation after the use of the hand-shaped tool. The authors proposed that morpho-functional similarities between the tool and the hand may determine the effect of specific tools on specific body-parts representations.

Yet, the same function can be achieved by using different tools. This, in turn, also requires different motor strategies to be applied and provides different sensory feedbacks, as when we loosen a screw with a coin or a screwdriver. Both the tool and the coin are controlled with the hand, but the sensori-motor constraints they impose on it are different. Is the representation of the hand capable of distinguishing between the two tools and thus reflect different forms of incorporation?

To address this question, we employed a paradigm that proved sensitive to tool-use-dependent changes of body schema (Cardinali, Brozzoli, et al., 2009; Cardinali, Frassinetti, et al., 2009). The rationale is that whichever the nature of the changes produced by tool-use, it would be reflected in the kinematic profile of free-hand movements performed after tool-use since they are planned and executed on the basis of the updated body representation. Here we assessed free-hand movements before and after use of two different hand-controlled tools: a pair of sticks, which were taped on participants thumb and index fingers, and a pair of pliers, which were acted upon by the same two fingers. These devices require different sensori-motor patterns to achieve the same function of grasping an object with elongated fingers, thus allowing to test whether what is incorporated is the tool morphology only or the sensori-motor control requirements.

2. Methods

Sixteen subjects took part in the study (7 males, mean age 24, 4 years; sd 3, 7). All had no previous history of neurological or psychiatric disorders, normal or corrected to normal vision. Two of them were left-handed and one ambidextrous as assessed through the Edinburgh Handedness Inventor (Oldfield, 1971). All gave their informed consent to participate in the study that was conducted according to the Declaration of Helsinki and approved by the ethics committee.

Subjects were comfortably seated at a table on which an object ($5 * 2 * 3$ cm) was placed and served as target object for all the reach-to-grasp movements. The starting point for the right hand consisted in a switch attached to a wooden block, positioned on the edge of the table close to the subject. The left hand rested on a similar switch on the left side of the same wooden block, 25 cm on the left of the right hand. All participants used their right hand, independently on their handedness. The distance between the starting position and the target object was kept constant throughout the experiment and was of 35 cm.

Subjects performed two sessions (with at least a 1-day interval), which differed only by the type of tool (pliers or sticks) subjects had to use. Both sessions were composed of a pre-tool-use phase, a tool-use phase and a post-tool-use phase and the order of the sessions was counterbalanced across the participants so that half of them used the Pliers first and then the Sticks and vice versa for the other half.

2.1. Tool use phase

The tool-use phase consisted of four blocks of twelve reach-to-grasp movements. In the Pliers session, subjects were asked to use 13-cm long plastic pliers. The pliers had to be controlled only by using the thumb and index finger (Supplementary Fig. 1A). Two spots were marked along the 'fingers' of the pliers to indicate the place where the thumb and index fingertips had to be positioned so that these participants' fingers will be elongated by 6 cm (i.e., almost doubling the fingers length). In the Sticks session, the same type of reach-to-grasp movement as in the Pliers session was requested (Supplementary Fig. 1B), but subjects had to use two separate wooden sticks attached to the thumb and index fingertips, to grasp the same object. Sticks were taped to the palmar side of the fingertips in such a way that the participants' thumb and index fingers were extended by the same amount (i.e., 6 cm) as in the Pliers session.

2.2. Pre- and post- tool use phases

In the pre- and post-tool-use phases, subjects were asked to perform two different movements with the right hand in separate blocks of twelve movements each: thumb-index finger grasping (TI) and thumb-middle finger grasping (TM). The order of blocks was counterbalanced. Subjects were told before the beginning of the block which grasp type they had to perform. They were asked to keep both hands in the starting pinch-grip position, i.e. the tips of the thumb and the finger-to-be-used in contact, pressing down