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Brain oxygenation patterns during the execution of tool use demonstration, tool use pantomime, and body-part-as-object tool use

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ABSTRACT

Divergent findings exist whether left and right hemispheric pre- and postcentral cortices contribute to the production of tool use related hand movements. In order to clarify the neural substrates of tool use demonstrations with tool in hand, tool use pantomimes without tool in hand, and body-part-as-object presentations of tool use (BPO) in a naturalistic mode of execution, we applied functional Near InfraRed Spectroscopy (fNIRS) in twenty-three right-handed participants. Functional NIRS techniques allow for the investigation of brain oxygenation during the execution of complex hand movements with an unlimited movement range. Brain oxygenation patterns were retrieved from 16 channels of measurement above pre- and postcentral cortices of each hemisphere. The results showed that tool use demonstration with tool in hand leads to increased oxygenation as compared to tool use pantomimes in the left hemispheric somatosensory gyrus. Left hand executions of the demonstration of tool use, pantomime of tool use, and BPO of tool use led to increased oxygenation in the premotor and somatosensory cortices of the left hemisphere as compared to right hand executions of either condition. The results indicate that the premotor and somatosensory cortices of the left hemisphere constitute relevant brain structures for tool related hand movement production when using the left hand, whereas the somatosensory cortex of the left hemisphere seems to provide specific mental representations when performing tool use demonstrations with the tool in hand.

1. Introduction

Human activities of daily living are characterized by a variety of skillfully actions with tools and objects. Knowledge about underlying brain functions is mainly based on studies of apraxia, i.e., the inability to execute learned purposeful movements (Donkervoort et al., 2000; Gazzaniga et al., 1967; Goldenberg, 2003; Heilman et al., 1982; Heilman and Rothi, 2003; Kimura, 1977; Laimgruber et al., 2005; Lausberg et al., 2003; Liepmann, 1905, 1908; Liepmann and Maas, 1907; Osiurak, 2013; Poeck, 1983; Rothi and Heilman, 1997). The results from apraxia research suggest that the conceptualization and execution of tool related actions crucially depend on left hemispheric functions (De Renzi and Lucchelli, 1988; Lausberg et al., 2003; Lewis, 2006; Liepmann, 1905, 1908, 1920; Rothi and Heilman, 1997). However, only a few studies have, thus far, investigated the neural correlates of tool related hand movements during production tasks (Choi et al., 2001; Hermsdorfer et al., 2007; Imazu et al., 2007; Johnson-Frey et al., 2005; Moll et al., 2000; Ohgami et al., 2004). The present study therefore aims to investigate brain functions that underlie tool related performances during actual movement production tasks in a naturalistic mode of execution.

Due to the typical methodological constraints in neuroimaging studies (e.g., restricted movement range of the arms), tool use pantomime executions have often been used as a proxy for tool use actions (Lewis, 2006). By a pantomime execution, the gesturer pretends to perform a motor action, i.e., pretending to brush the teeth with an imaginary toothbrush. However, neuroimaging data (Hermsdorfer et al., 2007; Imazu et al., 2007) and kinematic analyses of different manual aperture formations during natural and pantomimic grasping (Goodale et al., 1994; Westwood et al., 2000) indicate that natural hand movements, i.e., tool use actions, would rely on different neural substrates than pantomimed tool use movements. In fact, it has been proposed that neural activity associated with tool use pantomimes may reflect some levels of abstraction that may or may not be present during actual tool use (Lausberg et al., 2003).

Several brain imaging studies addressed tool use related hand movement production in healthy participants (Choi et al., 2001; Hermsdorfer et al., 2007; Imazu et al., 2007; Johnson-Frey et al., 2005; Moll et al., 2000; Ohgami et al., 2004). However, only two studies compared tool use pantomimes with actual tool use with the tool in hand (Hermsdorfer et al., 2007; Imazu et al., 2007). The use of chopsticks, relative to a control task such as watching the right hand when it was

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placed into the starting position activated several regions within both hemispheres, i.e., prefrontal, temporal, parietal, and occipital cortices (Imazu et al., 2007). When tool use was compared to tool use pantomimes, greater levels of activation in the left hemispheric postcentrally gyrus, and in the right hemispheric inferior parietal lobule, and cerebellum were observed (Imazu et al., 2007). However, Imazu et al. (2007) investigated right hand performances only. Thus, left hemispheric activations due to tool use could not be differentiated from executions with the contralateral hand. In a study by Hermsdorfer et al. (2007), participants performed tool use demonstration and tool use pantomime tasks using either the left or the right hand. The authors found that tool use demonstrations with tool in hand compared to tool use pantomimes lead to activations in temporal, parietal, and frontal sites. Within prefrontal and premotor cortices, Hermsdorfer et al. (2007) observed a strong bias towards the right hemisphere during tool use executions as compared to tool use pantomimes. However, a lateralization to the right hemisphere during tool use actions contradicts previous reports of a left hemispheric lateralization for processing objects or tools (Grafton et al., 1997). Furthermore, Hermsdorfer et al. (2007) showed that tool use tasks additionally activated sensory and motor areas when compared to tool use pantomime executions. However, due to the nature of their design, the authors could not differentiate whether these sensory–motor activations were driven by cognitive differences between tool use demonstrations and tool use pantomimes or merely represented the additional sensory stimulation elicited by holding the tool in hand during tool use demonstrations. In order to unambiguously detect whether the production of tool use demonstrations and tool use pantomimes relies on distinct cognitive representations in sensory–motor areas, the present study will control for sensory differences between conditions by introducing an additional 'hold' condition (see study design).

Goldenberg et al. (2007) emphasized that tool use pantomimes rely in particular on precentral cortices when performances are conducted in a naturalistic way of execution. However, naturalistic performances are not the case in fMRI studies in which participants are lying in a scanner with a restricted way of execution and no visual feedback from someone's own manual actions. Functional Near InfraRed Spectroscopy (fNIRS) techniques allow for the investigation of brain oxygenation during the execution of complex hand movements (Chang et al., 2014; Holper et al., 2009; Mehagnoul-Schipper et al., 2002; Wriessnegger et al., 2008) allowing less restricted movement ranges (Wolf et al., 2007), the participant's direct view on the acting hand(s), and the maintenance of the normal upright body position (Yoshino et al., 2013). Thus, fNIRS is particularly suitable for the investigation of naturalistic and complex tool use related hand movement production and has been therefore chosen for the present study. Since tool use demonstrations showed increased activation patterns in sensory cortices when compared to tool use pantomimes (Hermsdorfer et al., 2007; Imazu et al., 2007), we hypothesize that when demonstrating tool use with tools in hand but not when performing tool use performances with imaginary tools, i.e., during tool use pantomimes will lead to increased brain oxygenation within the postcentral cortex of the left hemisphere.

Furthermore, tool use pantomimes can differ whether they are performed by holding an imaginary object in hand or whether the imaginary object is integrated into the own body, i.e., a body-part-as-object (BPO) demonstration. For example, tool use pantomimes of hammering would usually be performed by forming the hand around an imaginary hammer whereas when demonstrating the use of scissors the gesturer would normally integrate the imaginary scissors into the own body by using the index and middle fingers to demonstrate the tool. In fact, patients with apraxia showed BPO executions as an error pattern of tool use pantomimes more often than healthy adults (Haaland and Flaherty, 1984; Lausberg et al., 2003; Ochipa et al., 1997; Poole et al., 1997). As the right hemisphere showed to particularly subserve BPO but not tool use or tool use pantomimes (Lausberg et al., 2003; Ohgami et al., 2004), we secondly hypothesize that tool use demonstrations and tool use pantomimes but not BPO presentations of tool use lead to increased oxygenation within left hemispheric cortices.

Thus, by using fNIRS to investigate neuronal correlates of tool related hand movement production the present study addresses whether the production of tool use demonstration, tool use pantomime, and tool use BPO demonstrations relies on distinct cognitive representations in sensory–motor areas when performed in a more a naturalistic way of execution. We control for sensory differences between conditions by introducing an additional 'hold' condition. We hypothesize that the left hemisphere, in particular premotor and sensory cortices subserve tool related hand movement production overall, however, only tool use demonstrations will show increased activation patterns in sensory cortices when compared to tool use pantomimes.

2. Materials and methods

2.1. Participants

Twenty-three participants (10 females, 13 males; age 29 $\pm$ 6 years [mean, SD]) took part in the study after written informed consent was obtained. All participants had normal or corrected to normal vision and no known history of any neurological or psychiatric disorder. The local Ethics Committee of the German Sports University Cologne approved the study. Handedness was established with two questionnaires, the Edinburgh Inventory (Oldfield, 1971) and a questionnaire currently used at the Montreal Neurological Institute (Crovitz and Zener, 1962). All participants were right-handed.

2.2. Training of the participants

To familiarize participants with the experimental setting (see below), participants practiced the task before the actual scanning session. An assistant named each tool and demonstrated its specific use and each gestural type of the three experimental conditions. During the training, most errors occurred during the BPO and pantomime conditions. Immediately, the participant received feed-back about his/her error. Thereby, the display of errors during the actual experiment was substantially reduced. If however, during the experiment an error occurred, this was noted by the experimenter and the trial was excluded from further analysis. To control for re-exposure effects during the experiment (van Turennout et al., 2000), each tool was presented at least twice in the training session.

2.3. Experimental setting and design

During the experiment, the participant was sitting in a dimmed room in a comfortable chair with armrests. Sixteen common tools were presented to the participant to elicit tool use actions: scissors, hammer, screw driver, box cutter, pencil, rattle, key, pizza knife, sponge, fork, spoon, knife, syringe, rake, stamp, and rubber.

Each tool was presented once in each of the three experimental conditions "*tool use demonstration*", "*tool use pantomime*" and "*tool use BPO*". Each condition was executed with the right and the left hand. In addition, an "*Execution*" and a "*Hold*" condition was implemented to account for the sensory stimulation during the tool use demonstration with tool in hand which is not present during BPO and pantomimes. By this, we could subtract out the sensory activation when holding an object in the hand ("*Execution*" condition minus "*Hold*" condition) in order to compare the three performance conditions. Together, this led to 12 different movement conditions. Fig. 1 shows all twelve movement variations for one exemplary tool (here: the scissors tool). Each movement condition comprised 2 randomized blocks, each of which included 8 trials (8 tools), resulting in a total of 16 trials per condition. Thus, the 16 tools were presented once in each condition. The blocks and trials were presented in a pseudo-random order with the following