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Cooperation in mind: Motor imagery of joint and single actions is represented in different brain areas

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ABSTRACT

In this study brain activity during motor imagery (MI) of joint actions, compared to single actions and rest conditions, was investigated using functional magnetic resonance imaging (fMRI). To the best of our knowledge, this is the first neuroimaging study which directly investigated the neural correlates of joint action motor imagery. Twenty-one healthy participants imagined three different motor tasks (dancing, carrying a box, wiping). Each imagery task was performed at two kinds: alone (single action MI) or with a partner (joint action MI). We hypothesized that to imagine a cooperative task would lead to a stronger cortical activation in motor related areas due to a higher vividness and intensification of the imagery. This would be elicited by the integration of the action simulation of the virtual partner to one's own action. Comparing the joint action and the single action condition with the rest condition, we found significant activation in the precentral gyrus and precuneus respectively. Furthermore the joint action MI showed higher activation patterns in the premotor cortex (inferior and middle frontal gyrus) compared to the single action MI. The imagery of a more vivid and engaging task, like our joint action imagery, could improve rehabilitation processes since a more distributed brain activity is found. Furthermore, the joint action imagery compared to single action imagery might be an appropriate BCI task due to its clear spatial distinction of activation.

1. Introduction

Motor imagery (MI) is the imagery of the body performing a movement in the absence of motor output. MI has been recognized for some years as one method for driving brain plasticity, skill acquisition and motor learning in numerous domains including sports training, brain-computer interface (BCI) research and motor rehabilitation, in particular with regard to the treatment of impairments after a stroke (Carrasco & Cantalapiedra, 2016; Guillot & Collet, 2008; Ietswaart et al., 2011; Kaiser, Kreilinger, Müller-Putz, & Neuper, 2011; Lee, Song, Lee, Cho, & Lee, 2011; Malouin, Richards, Durand, & Doyon, 2008; Neuper, Scherer, Wriessnegger, & Pfurtscheller, 2009; Schuster et al., 2011; Sharma, Baron, & Rowe, 2009; Silvoni et al., 2011). It is suggested that MI facilitates skill acquisition and motor learning in a manner similar to physical practice, resulting in plastic changes in the brain following repetitive mental practice (Grezes & Decety, 2001; Miller et al., 2010). Previous work on MI has already pointed out the significant influence of the imagined task on the neural response. Examples are the imagined body part (Ehrsson, Geyer, & Naito, 2003; Parsons, 2001; Szameitat, Shen, & Sterr, 2007) or the MI strategy, kinaesthetic vs. visual or first-person perspective vs. third-person perspective (Fourkas, Ionta, & Aglioti, 2006; Guillot et al., 2009; Hétu et al., 2013; Neuper, Scherer, Reiner, & Pfurtscheller, 2005). Whereas most of the reported MI studies used simple finger, hand and foot movements (Gerardin et al., 2000; Lotze & Halsband, 2006; Wriessnegger, Kurzmann, & Neuper, 2008) or finger to thumb opposition tasks (Porro et al., 1996; Solodkin, Hlustik, Chen, & Small, 2004) only a few deal with more complex tasks (Bakker, de Lange, Stevens, Toni, & Bloem, 2007; Guillot, Desliens, Rouyer, & Rogowski, 2013; Kalicinski & Raab, 2013; Olsson, Jonsson, Larsson, & Nyberg, 2008; Owen, Coleman, & Davis, 2006). Another study by Szameitat et al. (2007) showed that using more vivid and familiar tasks is more effective than a simple MI task. They investigated the MI of complex everyday movements such as hair brushing, dancing, playing cards or buttoning a shirt from a kinesthetic first-person perspective. Their findings support

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the suggestion that MI is effective since it activates a similar cortical network to that of physical training, but more importantly they pointed out the advantage inherent in the task used. That is using activities of daily life simplifies the process for the participants to generate a first-person imagery without prior training. This is especially relevant for clinical research and applications focusing on patients with motor impairments. For example, Page, Levine, Sisto, and Johnston (2001) and Page, Levine, and Leonard (2005) performed a randomized controlled study showing that stroke patients could improve their motor skills following motor imagery intervention. The patients who received motor imagery training improved significantly more on motor impairment tests than the control group. Furthermore Liu, Chan, Lee, and Hui-Chan (2004) showed that patients receiving mental imagery training in addition to physical therapy after experiencing a stroke showed significantly more improvement on tasks related to daily living than a control group. Additionally, motor imagery is the task most commonly used for induced brain activity based brain computer interfacing (BCI). A BCI translates physiological brain signals into an output that reflects the user's intent and provides severely motor-impaired users a new, non-muscular means for communication and control (Brunner et al., 2014; McFarland & Wolpaw, 2011; Neuper & Pfurtscheller, 2010; Pfurtscheller & Neuper, 2001; Wolpaw & Winter Wolpaw, 2012). There are different approaches for improving the performance of BCIs. Most studies focused on signal processing and feature extraction. However, BCI performance can also be improved by optimizing the user's control strategies by using more intuitive mental tasks for control (Curra & Stokes, 2003; Lotte, Larrue, & Mühl, 2013). For example, Friedrich, Neuper, and Scherer (2013) explored a range of seven different mental tasks (i.e. mental rotation, word association, auditory imagery, mental subtraction, spatial navigation, imagery of familiar faces and motor imagery) to investigate which pair of tasks can be reliably discriminated for BCI control. Their results indicated that combining different tasks, e.g. mental subtraction and motor imagery, led to increased performance. Furthermore, we (Wriessnegger, Steyrl, Koschutnig, & Müller-Putz, 2014) recently published a study where participants imagined sport activities, namely tennis or soccer, after a short physical session in both disciplines. We showed that already 10 min of training are sufficient to intensify motor imagery patterns in motor related brain regions. Beside its relevance in BCI research and clinical settings, MI has also been used by athletes and dancers who may benefit from matching imagery modalities to technical tasks in order to improve alignment and thereby avoid chronic injury (Girón, McIsaac, & Nilsen, 2012; Golomer, Bouillette, Mertz, & Keller, 2008; Schuster et al., 2011). Dance training in particular traditionally incorporates mental practice techniques often in cooperation with a partner, resulting in a kind of joint action motor imagery. This means the joint action often requires the adaptation of the action of two partners in space and time (Keller, 2012; Kourtis, Sebanz, & Knoblich, 2013; Sebanz, Bekkering, & Knoblich, 2006; Vesper, Butterfill, Knoblich, & Sebanz, 2010), such as when dancing the tango together, carrying a box, or riding on a see-saw. Few neuroimaging studies have investigated brain activation during joint actions (Bekkering et al., 2009; Newman-Norlund, Noordzij, Meulenbroek, & Bekkering, 2007), and none have investigated imagery of joint action. For example, in the study of Newman-Norlund, Bosga, Meulenbroek, and Bekkering (2008) participants lifted and balanced a virtual bar either alone or together with a partner. They found higher neuronal activation in the right inferior frontal gyrus indicating a link to the human mirror neuron system. This brain activation may reflect the simulation of other's actions by participants and integrating their own actions with those of their partners. There is currently only one behavioral study by Vesper et al. (2010) and colleagues linking motor imagery and joint action. In two behavioral experiments, they demonstrated that persons are able to integrate simulations of different parts in a joint action. The authors showed that persons can simulate both, their own and a partner's actions and are able to integrate these as predictions for coordination.

Inspired by this study we developed an experiment in which neural correlates of motor imagery of different joint actions, carrying of a heavy box, dancing the tango and riding on a see-saw, are investigated by fMRI. These joint actions were selected as being representative of common routines in everyday life. In contrast to the work of Vesper, Knoblich, and Sebanz (2014), who addressed the question of how motor simulations of one's own and another persons' action can be integrated, we focus on the neural correlates of the joint action MI task itself. To the best of our knowledge, we are the first to investigate which brain regions are involved in the imagery of joint actions compared to that of single actions. We use fMRI in this study because of its ability to investigate the whole brain's activation during the imagery tasks.

The aim of the study is twofold: First we will investigate joint action motor imagery in terms of a more user-appropriate motor imagery task for future BCI applications and rehabilitation purpose (e.g. stroke therapy). Second, we are interested in the neural correlates of the joint action imagery task itself. We hypothesize that a distributed neural network of motor related areas, like the supplementary motor area (SMA), primary motor cortex (PMC), cerebellum or prefrontal cortex (PFC) is involved due to the vivid imagery task in the joint and single action condition compared to the rest condition. Moreover, the imagery of performing a cooperative task (joint action condition) will elicit more pronounced cortical activation due to the intensification of the imagery, elicited by the integration of the action simulation of the virtual partner.

2. Methods

2.1. Participants

Twenty-one healthy right handed participants (16 male, 5 female, mean age 26.3 years, SD ± 4.4, range 21–35) took part in the experiment. Each participant was informed about the aim of the study and signed informed consent forms prior to the experiment. Additionally, each participant signed a further form after receiving information about risks and exclusion criteria of fMRI. The participants received compensation of € 7.50 per hour and a CD of their personal anatomical brain scan. The experiment was conducted in compliance with the World Medical Association Declaration of Helsinki and the protocol was approved by the Ethics Committee of the Medical University of Graz.

2.2. Stimulus material

The stimuli consisted of pictograms indicating 3 different conditions with 3 different stimuli each resulting in 9 pictograms for motor imagery. The stimuli were black pictograms showing two persons acting together (=joint action; JA), acting alone (=single action; SA) or they indicate no action (NA) such as simply sitting or standing together (Fig. 1). Since the imagery task needs to be performed from the 1st person perspective, women received the female pictograms (Fig. 1B) and men the male pictograms (Fig. 1A). In each pictogram one person was indicated by a dot. The participants had to imagine that they were this marked person from a first person perspective.

In the JA conditions, participants were asked to particularly focus on the joint action, whereas in the SA conditions they were to pay attention to their own performance from a 1st person perspective. The participants were carefully instructed to imagine just