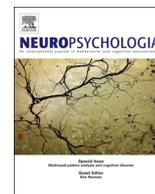




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Similarities between explicit and implicit motor imagery in mental rotation of hands: An EEG study



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ABSTRACT

Chronometric and imaging studies have shown that motor imagery is used implicitly during mental rotation tasks in which subjects for example judge the laterality of human hand pictures at various orientations. Since explicit motor imagery is known to activate the sensorimotor areas of the cortex, mental rotation is expected to do similar if it involves a form of motor imagery. So far, functional magnetic resonance imaging and positron emission tomography have been used to study mental rotation and less attention has been paid to electroencephalogram (EEG) which offers a high time-frequency resolution. The time-frequency analysis is an established method for studying explicit motor imagery. Although hand mental rotation is claimed to involve motor imagery, the time-frequency characteristics of mental rotation have never been compared with those of explicit motor imagery. In this study, time-frequency responses of EEG recorded during explicit motor imagery and during a mental rotation task, inducing implicit motor imagery, were compared. Fifteen right-handed healthy volunteers performed motor imagery of hands in one condition and hand laterality judgement tasks in another while EEG of the whole head was recorded. The hand laterality judgement was the mental rotation task used to induce implicit motor imagery. The time-frequency analysis and sLORETA localisation of the EEG showed that the activities in the sensorimotor areas had similar spatial and time-frequency characteristics in explicit motor imagery and implicit motor imagery conditions. Furthermore this sensorimotor activity was different for the left and for the right hand in both explicit and implicit motor imagery. This result supports that motor imagery is used during mental rotation and that it can be detected and studied with EEG technology. This result should encourage the use of mental rotation of body parts in rehabilitation programmes in a similar manner as motor imagery.

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1. Introduction

When attempting to judge the laterality of a picture of a human hand, it is believed that subjects mentally rotate an internal representation of their own hand in order to match it with the presented hand (Cooper & Shepard, 1975). Such a task is referred to as hand laterality test/judgement task (HLT) (Moseley, Butler, Beames, & Giles, 2012). A degree of mental effort applied in this task is proportional to the degree of mental rotation.

This rotation is similar to the mental rotation used for searching the congruency between two 3-D objects (Shepard & Metzler, 1971), in which subjects holistically, mentally rotate one of the 3D objects to match its orientation with that of the other (Cooper & Shepard, 1975). This holistic mental rotation model is supported by neuroimaging studies of mental rotation consistently finding the activation of the superior parietal lobule (SPL) and the intraparietal sulcus (BA 40).

These are brain areas known for implementation of spatial maps that code the position of body parts in relation to each other (Zacks, 2008; Sakata, Takaoka, Kawarasaki, & Shibutani, 1973; Bonda, Petrides, Frey, & Evans, 1995). Remarkably, activities in these regions are proportional to the degree of mental rotation performed (Gogos et al., 2010; Zacks, 2008; Weiss et al., 2009).

The hand mental rotation does not violate the bio-mechanical constraints imposed by the joints (Parsons, 1987a, 1987b, 1994). As shown by several chronometric studies, the time (reaction time, RT) it takes to mentally rotate the hand is proportional to the angular disparity between the current hand orientation and the new orientation (Shepard & Metzler, 1971; Parsons et al., 1995). Most interestingly, this time is also proportional to the time it would take to perform the movement physically (Parsons, 1994). These findings suggest that the neural system of movement is used to mentally rotate the hand in order to make a match with the presented hand picture. Since there is no overt movement, the neural system should resemble that of Motor Imagination/Imagery (MI) which is the mental simulation of motor action (Lotze & Halsband, 2006; Jeannerod, 2006). MI is neurally similar to physical execution of the action except that no movement

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is observed. During the mental rotation tasks, subjects are often unaware of imagination of movement. For this reason the term 'implicit MI' is used to describe the unrequested/unconscious imagination of movement during mental rotation tasks (Parsons, 2001; Parsons et al., 1995). Explicit MI therefore refers to a conscious motor imagination.

Implicit MI in mental rotation of body parts is an idea supported by many studies (Vingerhoets, de Lange, Vandemaele, Deblaere, & Achten, 2002; Cooper & Shepard, 1975; Parsons, 1987a, 1987b, 1994; Parsons et al., 1995; Wexler, Kosslyn, & Berthoz, 1998). Several brain areas known to be active during explicit MI have been found active during the mental rotation tasks (Zacks, 2008; Vingerhoets et al., 2002; Parsons et al., 1995). Parsons and colleagues used mental rotation induced by HLT to show that apart from the primary sensorimotor cortices, all the brain regions known to participate in the planning and execution of movement were activated by mental rotation of hands (Parsons et al., 1995).

So far extensive neuroimaging studies of mental rotation have been done using PET and fMRI which offer a high spatial resolution. EEG is a technology offering a higher temporal and frequency resolution which is useful in studying the dynamic brain processes. Time-frequency analysis of EEG is a well-established technique used to study MI (Pfurtscheller, Scherer, Müller-Putz, & Lopes da Silva, 2008). Although hand mental rotation is claimed to involve MI, the time-frequency characteristics of mental rotation have never been compared with those of MI. Such an analysis is necessary to establish the relationship between MI and hand mental rotation. Previous 3D objects and alphanumeric based mental rotation studies (Riečansky & Katina, 2010; Gill, O'Boyle, & Hathaway, 1998) using EEG did not describe the complete time-frequency characteristics.

In a recent study, Chen and colleague (Chen, Bin, Daly, & Gao, 2013) only analysed an early induced EEG activity during hand mental rotation induced by HLT. Their experimental design involved subjects pressing buttons with their hands to indicate their judgements. Since the subjects were believed to be mentally rotating their hands, pressing the button with the same hands could interfere with the results. An important, yet unanswered question that would further confirm similarity between explicit and implicit MI is whether it is possible to discriminate between left and right mental rotation using EEG signal recorded during a hand mental rotation task such as HLT.

The present study has three main objectives. (1) To study the time-frequency dynamics and spatial localisation of sensorimotor activities during mental rotation of hands induced by HLT. (2) To test whether it is possible to discriminate between left and right hand mental rotation using EEG recorded during HLT. (3) To compare time-frequency responses over the sensorimotor cortices between implicit MI (in HLT) and explicit MI. The knowledge gained by studying the above is relevant to understanding the mental rotation process. Furthermore establishing that implicit MI is involved in mental rotation and that it is similar to explicit MI can open new areas of application in which mental rotation induced implicit MI can be used to complement explicit MI used in rehabilitation of movement (Cramer, Orr, Cohen, & Lacourse, 2007; Dijkerman, Ietswaart, Johnston, & MacWalter, 2004; Driskell, Copper, & Moran, 1994; Grangeon, Revol, Guillot, Rode, & Collet, 2012). Patients who find it difficult to perform explicit MI due to loss of proprioception/sensation for example following incomplete spinal cord injury may use the implicit MI automatically invoked in the brain to activate the motor cortex in a similar manner as explicit MI in rehabilitation. Hand mental rotation induced with HLT is already in use in the treatment of complex regional pain (Moseley et al., 2012; Walz et al., 2013; Bowering et al., 2013) and its use is expected to widen (Moseley et al., 2012).

2. Methods

2.1. Data collection

2.1.1. Subjects

Fifteen right handed (Edinburgh handedness inventory (Oldfield, 1971) mean, $+76 \pm 19$) healthy subjects (mean age 24.9 ± 5.0 , 6 females) volunteered for this study. The subjects gave their informed consents. The study was approved by the University ethics committee.

2.1.2. MI trials

A cue-based paradigm implemented with rtsBCI Scherer was used. A trial lasted for 6000 ms. At the beginning of a trial ($t = -3000$ ms), the user was presented with a blank screen.

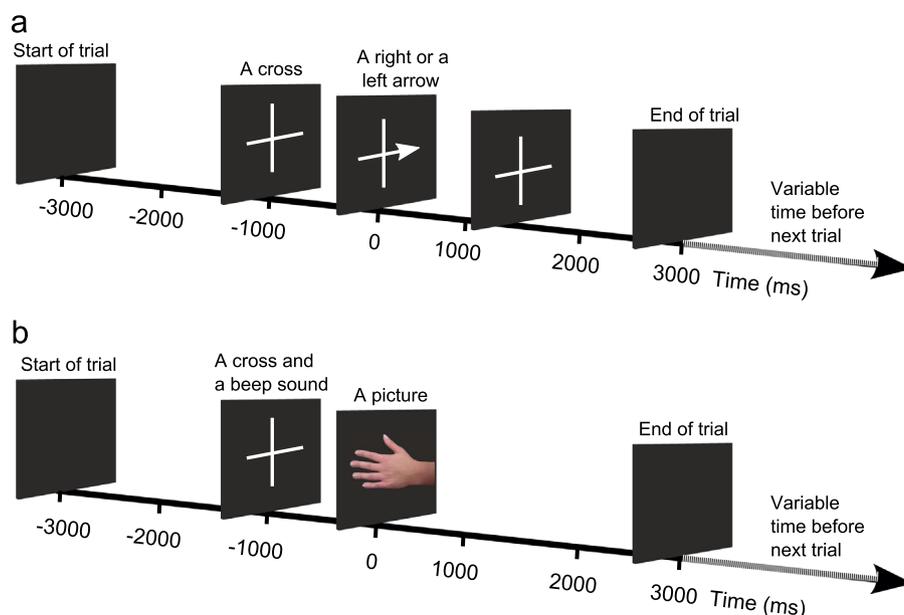


Fig. 1. The sequence of events for (a) MI and (b) HLT trials.

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