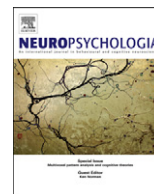




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Neuropsychologia

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

Mu-rhythm changes during the planning of motor and motor imagery actions[☆]

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ARTICLE INFO

Article history:

Received 26 November 2012

Received in revised form

5 February 2013

Accepted 14 February 2013

Available online 24 February 2013

Keywords:

Motor imagery

Mu activity

Sensitive-motor cortex

Pre-motor cortex and supplementary

motor cortex

Visual-motor task

ABSTRACT

Motor imagery is a mental representation of motor behavior which has been widely used to study the cognitive basis of movement. The assumption that real movements and motor imagery (virtual movements) use the same neurobiological basis has been questioned by functional magnetic resonance data. The functional similarity in the planning of real and virtual movements was studied here by analyzing event-related EEG recordings of the Mu-activity in the sensitive-motor cortex, pre-motor cortex and supplementary motor cortex. A visual stimulus (an arrow) which displayed the information needed for planning a motion (which can be executed or imaged later after the display of a second stimulus) induced a short-lasting phase-locked Mu-response (PLr) which was wider and more wide-spread when it was used for the motor planning of real or virtual movements than when it was passively watched. The phase-locked Mu-response was accompanied by a persistent decrease of the Mu-rhythms which were not phase-locked to stimuli (NPLr), a response which also was more marked and generalized when stimuli were used for motor planning than when they were passively observed. PLr and NPLr were similar during motor testing and imagery testing, suggesting that both tasks activated the Mu rhythms to a similar degree. This congruency between real and virtual movements was observed in the three cortical areas studied, where the amplitude, latency and duration of the phase-locked and non-phase-locked Mu response was similar in both cases. These noticeable similarities support the idea that the same cortical mechanisms are recruited during the planning of real and virtual movements, a fact that can be analyzed better when an event-related paradigm and a high time-resolution method are used.

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1. Introduction

Motor imagery (MI) is a dynamic mental representation of motor behavior which is not accompanied by real movements (virtual movement). As virtual movements show many similarities with real movements and they are not interfered with by variables involved in the execution of real movements (e.g. somatosensory stimuli) (Sabate, Gonzalez, & Rodriguez, 2007; Sabate, Llanos, & Rodriguez, 2008), MI has been widely used to study the cognitive basis of movement. The similarity of cognitive functions involved in real and virtual movements has been

supported by chronometric studies showing that both movements consume the same execution time and use the same neurobiological basis. The time needed to execute a motor pattern is similar to that needed for its MI (Abbruzzese, Trompetto, & Schieppati, 1996; Crammond, 1997; Sirigu et al., 1996), and this increases in both cases with the complexity and accuracy of the task (Fitts' law) (Decety & Lindgren, 1991; Dominey, Decety, Broussolle, Chazot, & Jeannerod, 1995; Jeannerod & Frak, 1999; Sirigu et al., 1996). This real–virtual congruency has been observed in normal subjects under different conditions (e.g. during ageing) (Morales, Dopico, Sabate, Gonzalez-Hernandez, & Rodriguez, 2007; Sabate, Gonzalez, & Rodriguez, 2004) and in patients with different brain lesions (e.g. stroke and Parkinson disease) (Cramer, Finklestein, Schaechter, Bush, & Rosen, 1999; Dominey et al., 1995; Gonzalez, Rodriguez, Ramirez, & Sabate, 2005; Morales et al., 2007; Sirigu et al., 1996; Thobois et al., 2000). However, this real–virtual congruency decreases in some circumstances. For instance, congruency decreases occurs when

[☆]This work was supported by the Ministerio de Educación y Ciencia del Gobierno Español (SAF2007-61784) and CIBERNED.

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movements are automatically executed without conscious supervision (Sabate et al., 2004), or when they need an “on line” adjustment during their execution (Rodriguez, Llanos, & Sabate, 2009). In addition, the real–virtual congruency of patients with brain damage may be transiently lost just after acute lesion, requiring a time interval where the motor practice (e.g. 1–2 weeks after stroke) to restore the pre-lesion congruency (Sabate et al., 2007). These data suggest that similarities between real and virtual movements could be the result of an active process (which scans the competence of elements involved in the motor behavior to adjust motor planning and virtual imagery to the real capability of the motor system) (Sabate et al., 2007) more than the result of using the same neuronal basis (the common-basis hypothesis). Thus, the functional similarity between real and virtual movements and the neuronal networks involved in each case are still a matter of debate.

The experimental method most frequently used to test the common-basis hypothesis for real vs. virtual movements is functional magnetic resonance (fMRI). This method has provided data showing that areas such as the primary sensorimotor cortex (SMc), pre-motor cortices (PMc), and supplementary motor cortex (SpMc) are recruited by both real movements and their MI (Decety, 1996; Gerardin et al., 2000; Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Hanakawa et al., 2003; Lotze et al., 1999; Naito et al., 2002; Porro, Cettolo, Francescato, & Baraldi, 2000; Porro et al., 1996; Sirigu et al., 1996; Stephan et al., 1995), thus supporting the common-basis hypothesis. However, the activation degree (Gerardin et al., 2000; Hanakawa et al., 2003; Michelon, Vettel, & Zacks, 2006) and the spatial distribution of the activation within these areas (Rodriguez, Muniz, Gonzalez, & Sabate, 2004) can be different for real and virtual movements. In addition, there are fMRI studies showing that areas activated during MI and those activated during motor performance of the same action do not always completely overlap (Binkofski et al., 2000; Ruby & Decety, 2001; Sirigu & Duhamel, 2001; Solodkin, Hlustik, Chen, & Small, 2004). This imperfect overlapping could be associated to the differing abilities of subjects for imaging movements (Guillot et al., 2008), but also to the limits of experimental methods used to study the brain activity during real and virtual movements. The fMRI has a high spatial resolution but a low temporal resolution (s), which limits its application to the study of fast motor tasks which, as occurs with MI, can be performed in short time-intervals (ms). Considering that a low time-resolution could produce ambiguous data with puzzling interpretations, the biological basis of real and virtual movements was studied here by using electroencephalography (EEG), a method with a low spatial resolution but an excellent time-resolution (ms). Thus, the aim of this work was to study the electrophysiological behavior of the motor cortex during the planning of real and virtual movements.

The SMc, PMc and SpMc display a typical EEG oscillation known as the Mu rhythm. The Mu rhythm is a short-lasting (0.5–2 s) wave in the alpha range (8–12 Hz) which is recorded at rest (Chatrian, Petersen, & Lazarte, 1959; Gastaut & Bert, 1954; Muthukumaraswamy & Johnson, 2004; Penfield, 1954; Pfurtscheller & Lopes da Silva, 1999; Pineda, 2005) and attenuated by voluntary movements (Babiloni et al., 1999; Leocani, Toro, Zhuang, Gerloff, & Hallett, 2001; Salenius, Schnitzler, Salmelin, Jousmaki, & Hari, 1997; Salmelin & Hari, 1994). These facts initially suggested that the Mu wave is an “idling” rhythm which, in the motor cortex, reflects the same “nil-work” status proposed for the α -wave in the occipital cortex (idling hypothesis) (Kuhlman, 1978; Pfurtscheller, Stancak Jr., & Neuper, 1996). However, a Mu rhythm activation has been also reported during the execution of different tasks (Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999; Krause et al., 2000), thus

suggesting that the Mu wave is a mechanism for improving information processing (processing hypothesis) (Basar, Basar-Eroglu, Karakas, & Schurmann, 2000, 2001; Linkenkaer-Hansen, Nikulin, Palva, Ilmoniemi, & Palva, 2004; Palva & Palva, 2007; Sabate, Llanos, Enriquez, & Rodriguez, 2012). In fact, the Mu rhythm could improve data processing when its phase is modified by the task onset, inhibiting the data processing when it is not phase-locked with the task (Sabate et al., 2012). The task sensitivity of the Mu-rhythm has been used here to compare the functional activity of the motor cortex during real movements with that recorded during their motor imagery. The Mu rhythm can change with visual stimuli (Koshino & Niedermeyer, 1975; Pfurtscheller, 1992; Pfurtscheller & Lopes da Silva, 1999), particularly when they are used to trigger the planning of new motor patterns (Sabate et al., 2012). This sensitivity of the Mu rhythm to visual stimuli has been used here to segregate the time interval used to plan movements from the interval used to execute the planned movements (event-related paradigm). Finally, the study was focussed on comparing Mu activity during the planning of real and virtual movements.

2. Material and methods

A total of 11 men ranging between 23 and 58 years of age were studied. All subjects were in good health, had no prior history of cerebral disease or medical treatment which might influence motor performance, and had adequate cognitive and visual-motor functions to perform the test. All subjects were right-handed according to the Edinburgh Inventory of handedness (Oldfield, 1971). The study was approved by the local Research Ethics Committee.

2.1. Procedure

Tests were performed with the right hand in a sound-attenuated and temperature regulated (22 ± 1 °C) room which was lit by homogeneous white light and that provided stable and reproducible environmental conditions. During the experiments, the subjects sat comfortably in a chair in front of a computer screen (60 cm) which showed the visual stimuli (Evoke, ANT Software, Enschede, The Netherlands).

Three tests were conducted. The motor test involved the display of two successive visual stimuli, a first stimulus (an arrow) indicating the direction of the finger motion to be performed when a second stimulus (a large dot) gave the signal to execute the movement. In the imagery test, the first stimulus (an arrow) indicated the direction of the finger motion to be performed by MI after the display of the second stimulus (a large dot). The subjects saw the same stimuli without performing any tasks in the passive test. Only the Mu-response to the first stimulus was evaluated (motor response started ≈ 2000 ms after the first stimulus and ≈ 400 ms after the second stimulus). In other words, the active test consisted of preparing to move the thumb in a direction which depended on the instruction given by the first stimulus (a red arrow pointing up-down-right-left). The thumb movement could not be initiated until a large red dot (second stimulus) replaced the first stimulus on the computer screen. The instructions to the subjects used in the active test were as follows: “Please move your thumb (initially placed on a central point of a joystick) to press the button located above, below, to the right or to the left of your thumb (30 mm from the central button), and return your thumb to the initial position as fast as possible. The same task was performed in the imagery test but, in this case, instead of making movements the subjects should perform their motor imagery. Motor imagery consisted of imagining the performance of motor sequences and the kinesthetic sensations associated with it while keeping the finger still. Subjects were informed that “visual imaginations” of the finger movement (an imaginary watching of one’s own hand in motion) and modifications in the muscle tone during the MI task (a simultaneous contraction of the flexor and extensor muscles of the hand) were not permitted. All subjects reported sensations associated with virtual movements but none of them showed evidence of real movements (evaluated with a goniometer for finger movement; Penny and Giles; Christchurch, UK). In each trial, the specific button to be pressed (or imagined to be pressed) was indicated by the direction of the arrow on the screen, but the subjects were not allowed to move their right thumb (or to imagine moving it) until the arrow was replaced by a large red dot”, and a joystick was used for this task. At the beginning of the task, the tip of the right-thumb was touching a button located exactly in the middle of the four surrounding buttons serving as the targets of the movements. The task of the passive test consisted of watching the same stimuli but doing nothing with them (the tip of the right-thumb continued to touch the middle button). In the active and imagery tests, the shape of the first stimulus (an arrow pointing in a

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