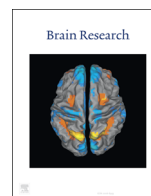




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Inferior frontal gyrus links visual and motor cortices during a visuomotor precision grip force task



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ARTICLE INFO

Article history:

Received 22 April 2016

Received in revised form

6 September 2016

Accepted 7 September 2016

Available online 15 September 2016

Keywords:

Visuomotor integration

Coherence

Functional connectivity

Inferior frontal gyrus

Magnetoencephalography

ABSTRACT

Coordination between vision and action relies on a fronto-parietal network that receives visual and proprioceptive sensory input in order to compute motor control signals. Here, we investigated with magnetoencephalography (MEG) which cortical areas are functionally coupled on the basis of synchronization during visuomotor integration. MEG signals were recorded from twelve healthy adults while performing a unimanual visuomotor (VM) task and control conditions. The VM task required the integration of pinch motor commands with visual sensory feedback. By using a beamformer, we localized the neural activity in the frequency range of 1–30 Hz during the VM compared to rest. Virtual sensors were estimated at the active locations. A multivariate autoregressive model was used to estimate the power and coherence of estimated activity at the virtual sensors. Event-related desynchronization (ERD) during VM was observed in early visual areas, the rostral part of the left inferior frontal gyrus (IFG), the right IFG, the superior parietal lobules, and the left hand motor cortex (M1). Functional coupling in the alpha frequency band bridged the regional activities observed in motor and visual cortices (the start and the end points in the visuomotor loop) through the left or right IFG. Coherence between the left IFG and left M1 correlated inversely with the task performance. Our results indicate that an occipital-prefrontal-motor functional network facilitates the modulation of instructed motor responses to visual cues. This network may supplement the mechanism for guiding actions that is fully incorporated into the dorsal visual stream.

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1. Introduction

The ability to continuously adapt motor output to sensory feedback is crucial to everyday functioning and is utilized in tasks ranging from simple to more complex. The continuous adjustment

of a force to a visual feedback requires the integration of sensory input and motor output, and it involves the continuous integration of activity from different frontal, parietal, and sensorimotor brain regions in an extended brain network (Floyer-Lea and Matthews, 2004; Vaillancourt et al., 2006).

Previous attempts to understand the electrophysiology of the brain network underlying visuomotor integration have shown a decrease in oscillatory activity, in particular in the alpha and lower beta (8–21 Hz) frequency bands (Classen et al., 1998; Rearick et al., 2001; Kranczioch et al., 2008; Rilk et al., 2011). These power changes were localized by electroencephalography (EEG) in central, parietal, and occipital brain areas (Classen et al., 1998; Rilk et al., 2011). The communication among these areas was assumed to be implemented through a long-range synchronization mechanism that involves the coherence of neuronal activity across the involved distant brain regions in the alpha (Classen et al., 1998; Chen et al., 2003; Rilk et al., 2011; Mylonas et al., 2016), beta and gamma frequency-bands (Aoki et al., 1999; 2001; Babiloni et al., 2006; Baker et al., 1999; Lee, 2003; Ohara et al., 2000; Mylonas et al., 2016).

Abbreviations: AIP, anterior intraparietal area; DLPFC, dorsolateral prefrontal cortex; fMRI, functional magnetic resonance imaging; IFG, inferior frontal gyrus; IFS, inferior frontal sulcus; IOFF, inferior occipito-frontal fascicle; IPS, intraparietal sulcus; M, pure motor; M1, hand motor cortex; MEG, magnetoencephalography; MVAR, multivariate autoregressive; PCM, probabilistic cytoarchitectonic maps; PET, positron emission tomography; PMV, ventral premotor cortex; ROI, regions of interest; SAM, Synthetic Aperture Magnetometry; SII, secondary somatosensory cortex; SnPM, Statistical nonParametric Mapping; SLF, superior longitudinal fasciculus; SPL, superior parietal lobe; TMS, transcranial magnetic stimulation; V, pure visual; VM, visuomotor task

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<http://dx.doi.org/10.1016/j.brainres.2016.09.011>

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Despite a fair understanding of the neural mechanisms underlying visual and motor systems, the neurophysiological mechanisms which are involved in sensory-motor integration are still unclear. Sensory-motor integration refers to the ability to coherently organize bodily sensations and transfer them into motor commands. The goal of this study is to investigate the neurophysiological patterns of local, *intra*regional, and *inter*regional oscillatory activity related to sensory-motor integration in a visuomotor precision pinch force task, and to correlate this activity with behavioral performance. The study focuses on the precision pinch because it is a physiologically particularly important motor action. It has been developed in primates for the manipulation of small objects with the tips of the thumb and fingers, and requires independent finger movements that involve fine control of the directions and magnitudes of fingertip forces (Flanagan et al., 1999; Johansson et al., 1996). These precise movements are often guided by somatosensory, proprioceptive, and visual feedback. We hypothesize that sensorimotor integration will be executed through a complex functional network that involves primary sensory and motor areas as well as secondary integration areas in the frontal and parietal cortex. We assume that the spatially distributed information between these areas will be integrated into coherent representation states through synchronized rhythmic neural firing, i.e. the integration of distributed information into a unified representation (Gray et al., 1989; Singer, 1999; von der Malsburg, 1999).

To test our hypothesis, we recorded magnetoencephalography (MEG) signals from healthy adult individuals while performing a visuomotor precision pinch force task (VM) as well as during two control conditions involving either pure motor (M) or pure visual (V) tasks. During the VM task, adult participants had to continuously adjust the isometric pinch force with which a manipulandum was held between their right index finger and their thumb (Fig. 1). The requested and the generated force were presented as a visual signal to the participants in order to provide continuous feedback about the accuracy of the generated force. Performance during the VM task was quantified as the continuous tracking error. MEG data analysis was performed on the ongoing cortical activities. By using a beamformer source-localization technique, we estimated the task-related brain oscillatory power changes between 1 and 30 Hz during VM compared to rest. The

power changes were described as event-related synchronization (ERS) or event-related desynchronization (ERD) depending on whether oscillatory power was increased or decreased during the task relative to rest (Aranibar and Pfurtscheller, 1978). Virtual sensors were then estimated at the active locations. A multivariate autoregressive model was used to estimate the power and coherence of estimated activity at the virtual sensors for all three tasks (VM, M, and V). The correlation between the VM task performance and the coherence of brain activity time-courses was also estimated.

2. Results

2.1. Brain source activity estimated by source-reconstruction technique

Fig. 2 shows the ERD during the VM compared to rest as revealed by group volumetric statistical analysis ($p < 0.05$) with peak locations summarized in Table 1. No significant ERS were observed. For the sake of clarity, we will refer to the brain regions with significant ERD as “active sources” since ERD is generally related to increased neural activation (Pfurtscheller and Lopes da Silva, 1999; Singh et al., 2002; 2003; Neuper et al., 2005).

Active sources were observed (see Table 1): (i) around the rostral part of the left inferior frontal sulcus (this spot was well rostral to the probabilistic location of cytoarchitectonic area BA45 and likely corresponded to BA46 and/or BA10 and will be referred to as rostral IFG - see Fig. 2, upper left panel), (ii) in the middle portion of the right IFG falling within the rostral boundaries of BA45 (see Fig. 2, upper left panel), (iii) around the parietal opercular region, most likely representing activation within the secondary somatosensory cortex (SII), corresponding to cytoarchitectonic OP4 subdivision, (iv) in the occipital convexity bilaterally, corresponding to BA18 cytoarchitectonic subdivision, and representing activation within early visual areas (see Fig. 2, upper right panel), (v) in the left precentral sulcus corresponded to the primary motor cortex (M1) within the BA4 (see Fig. 2, lower left panel), and (vi) around the right superior parietal lobe (SPL) that corresponded to cytoarchitectonic area BA7 (see Fig. 2, lower right

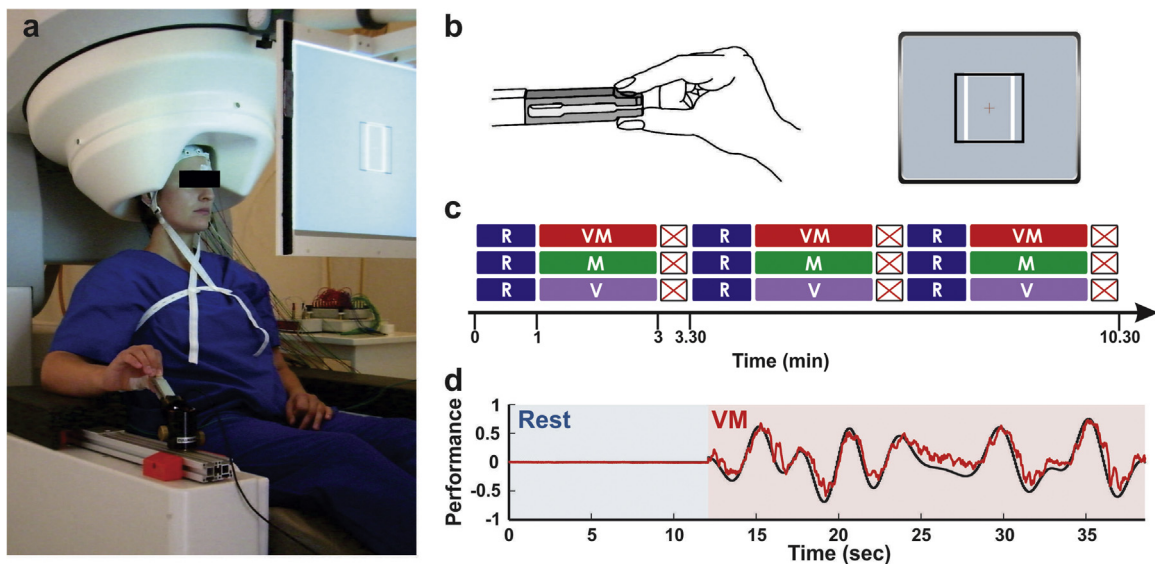


Fig. 1. Experimental setup and design. (a) Participant during performing the VM task. (b) Schematic illustration of the precision pinch sensor (left) and the presented visual stimulus (right). The requested force was indicated by a black rectangle projected on the screen. A white rectangle varied also horizontally in size. In case of a perfect match between the requested and the generated force the white rectangle was exactly superimposed onto the black one. (c) Schematic representation of the experimental protocol. (d) Example of the VM performance (for one representative subject). Sample of the produced isometric contraction force for 38 s over-plotted on the requested force during rest and VM (arbitrary units). The correlation between the two signals was 0.91 for this subject.

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