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Targeted reinforcement of neural oscillatory activity with real-time neuroimaging feedback

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ABSTRACT

Biofeedback and brain-computer interfacing using EEG has been receiving continuous and increasing interest. However, the limited spatial resolution of low-density scalp recordings is a roadblock to the unequivocal monitoring and targeting of neuroanatomical regions and physiological signaling. This latter aspect is pivotal to the actual efficiency of neurofeedback procedures, which are expected to engage the modulation of well-identified components of neural activity within and between predetermined brain regions. Our group has previously contributed to demonstrate the principles of real-time magnetoencephalography (MEG) source imaging. Here we show how the technique was further developed to provide healthy subjects with region-specific neurofeedback to modulate successfully predetermined components of their brain activity in targeted brain regions. Overall, our results positively indicate that neurofeedback based on time-resolved MEG imaging has the potential to become an innovative therapeutic approach in neurology and neuropsychiatry.

Introduction

Brain-computer interface (BCI) techniques are currently gaining interest as therapeutic and assisted-living devices (Kaiser et al., 2011; Manyakov et al., 2011; Shindo et al., 2011; Tam et al., 2011). In a nutshell, BCI technology consists in establishing a form of communication between brain activity and an external device. Traditionally, most of the interest has been focused on using this connection in a unidirectional way to steer and control external objects such as motorized wheelchairs, computer interfaces or game consoles (Vallabhaneni et al., 2005). More recently, there has been a new focus on using BCI to provide feedback based on the subject's own brain activity. For example, commercial providers now offer basic BCI solutions to assist people in practicing meditation or in promoting concentration and vigilance (Lutz et al., 2009). Preclinical research studies have also argued in favor of BCI with feedback as a potential therapeutic approach to multiple neurological and psychiatric conditions (Dayan and Cohen, 2011; Lubar et al., 1995; Sanes and Donoghue, 2000; Sterman, 1981; Sterman and Egner, 2006). A possible approach consists in providing biofeedback indexed on the participant's own brain activity, thereby enabling a form of neurofeedback. BCI and neurofeedback commonly make use of scalp electroencephalography (EEG) electrodes to access brain activity. In the case of interfacing users with ambulatory machines or personal applications, the portability and cost-efficiency of the EEG are essential. However, when considering potential therapeutic applications, the highest priority is in the ability to provide feedback indexed on predetermined components of the patient's brain activity generated within targeted brain regions. Unfortunately, the spatial smearing caused by the skull bone in particular impedes the spatial resolution of scalp EEG across a wide spectrum of oscillatory components (Schaul, 1998; Varela et al., 2001). Consequently, EEG scalp signals are of poor spatial specificity and sensitivity to the local neural processes that need to be monitored and quantified during neurofeedback.

Recently, it has been shown that magnetoencephalography (MEG) can be used as a real-time neurofeedback device, enabling subjects to modulate ongoing or task-related brain rhythms associated with awareness, attention, and motor performance (Birbaumer and Cohen, 2007; Mellinger et al., 2007; Wang et al., 2010). However so far, MEG-based neurofeedback has been only indexed on MEG sensor time series (Egner et al., 2004; Vernon et al., 2003). As such, the existing MEG approaches are akin to EEG's because extra-cranial MEG sensor data is also impeded – although to a lesser extent than EEG – to the spatial smearing of contributions from multiple brain areas (Baillet et al., 2001; Gross and Schoeffelen, 2009).

In the present contribution, we demonstrate how real-time MEG source imaging can be used to access ongoing neural activity within predefined brain regions. Our group had previously demonstrated the technical feasibility of real-time MEG source imaging with an engineering perspective (Sudre et al., 2011). This previous study, however, did not investigate the possible effects of longitudinal neurofeedback training with this technique. In essence, we present here a proof of concept and feasibility that may yield new avenues of future therapeutic

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research in a multiplicity of neurological and neuropsychiatric disorders. The technique of real-time MEG source imaging makes it possible to provide subjects with feedback on the time-resolved activity of targeted brain regions. In the context of multiple-session neurofeedback training, advancing the signal-capture technique from the scalp to the scale of the brain regions may improve the specificity and therefore, the efficiency of the approach. We therefore demonstrate in the present study that 1) it is possible to provide subjects with region-specific real time neurofeedback and 2) subjects can be successfully trained to modulate components of oscillatory neural activity within the targeted brain regions.

Methods

Anatomical data and targeted neurofeedback regions

One healthy female and one male volunteer (age 25 and 41 years) participated in a longitudinal MEG neurofeedback training protocol. To enable cortically-constrained MEG source imaging, a T1-weighted MRI scan of the participant's brain was obtained (General Electric Signa 1.5-T, IR FSPGR, 240 × 240 mm field of view, 124 1.3-mm axial slices). The individual cortical surfaces were extracted from the MRI volume data using the automatic segmentation pipeline available in Brainvisa (http://brainvisa.info), with default parameter settings. The scalp and cortical surface envelopes were imported into Brainstorm, the open-source software environment we used for offline MEG data analysis (Tadel et al., 2011). The high-resolution triangulated cortical surfaces (~75,000 vertices) were down-sampled with Brainstorm to about 15,000 vertices, to serve as image supports for MEG source imaging (Baillet et al., 2001).

The individual MRI volumes and cortical surfaces were also used for defining the anatomical regions of interest (ROIs) targeted by the neurofeedback training (Fig. 1): We selected the bilateral dorsal aspect of the superior parietal lobule, anterior and posterior aspects of the central sulcus, and aspects of the dorsomedial frontal cortex (pre-supplementary motor area: preSMA). In terms of functional relevance, these brain regions were previously identified to be involved in motor imagery, a possible strategy for subjects to modulate online neurofeeback indices (Buch et al., 2008; Dechent et al., 2004; Ehrsson et al., 2003; Lotze and Halsband, 2006; Munzert et al., 2009). Overall the definition of the ROIs was empirical in both subjects. The goal was to test whether the activity in roughly defined brain regions could be arbitrarily modulated by neurofeedback training. In that respect, and because this is a longitudinal study, results should be considered individually. At the extreme, we could have selected anatomically different sets of regions in both subjects.

Neurofeedback training protocol

The two subjects participated in a multi-day training protocol consisting of 9 (1 baseline reference and 8 with neurofeedback) sessions in the MEG, scheduled over 14 days. The timeline of the training paradigm is illustrated in Fig. 2.

The MEG recording parameters were for an Elekta/Neuromag Vectorview system (204 planar gradiometers, 102 magnetometers), with data sampling rate set at 2000 Hz. Electro-oculogram (EOG) and -cardiogram (ECG) leads were applied to capture eye blinks and heartbeat artifacts, following guidelines of good MEG practice (Gross et al., 2013). Visual presentations were displayed on a back-projection screen.

All 9 sessions began with a 2-minute empty-room MEG recording, to capture daily environmental noise statistics (sample data covariance across MEG channels) that were used for MEG source modeling (see below).

The baseline reference session (Session 1) consisted of 2 runs, each with 10 trials, interspersed with 5 to 10 s of rest (eyes open). Each trial entailed 30 s of a pre-recorded movie presentation of a color-changing disk (as later used to provide actual neurofeedback). The disk's color was updated every 500 ms, ranging from dark red to bright yellow. To maintain vigilance, subjects were instructed to silently count the number of color changes during each trial.

At the beginning of each of the 8 neurofeedback training sessions (Session 2–9), subjects were instructed that they would need to find a strategy to change the color of the presented disk to the brightest levels of yellow color, and to maintain these levels as long as possible. They were indicated that the color of the disk was indexed on their ongoing brain activity. After the last training session was completed (Session 9), subjects were asked to report on the nature of the strategy that they had developed.

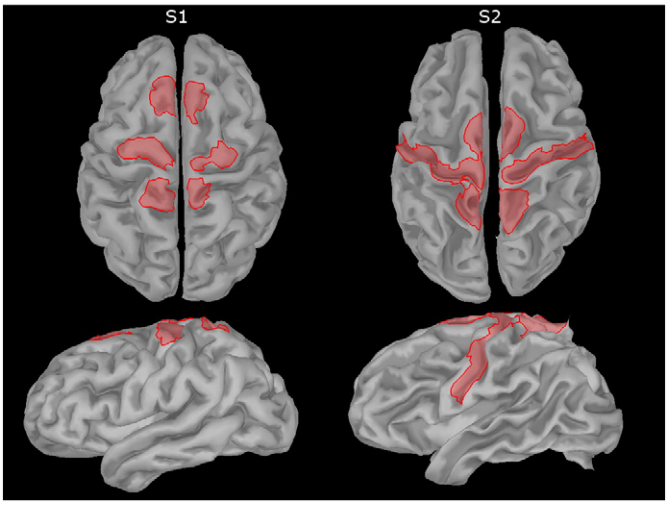

Fig. 1. Targeted regions of interest for MEG neurofeeback (in red): The bilateral dorsal aspect of the superior parietal lobule, anterior and posterior aspects of the central sulcus, and the dorsomedial frontal cortex (pre-supplementary motor area, preSMA) were manually delineated onto the cortical surface of the two participants: S1 and S2. The dark grey areas indicate sulcal folds; light grey areas represent gyral crowns. The cortical surfaces are shown with spatial smoothing applied to facilitate 3D visualization of the cortical manifold.

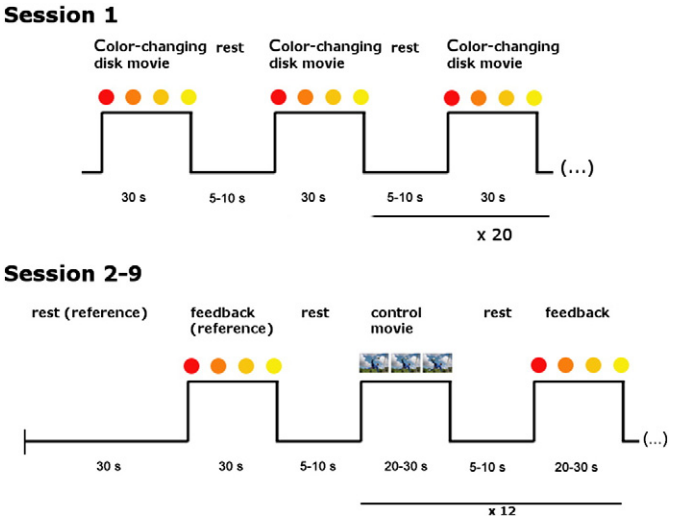

Fig. 2. Neurofeedback training protocol: On Session 1, subjects were only presented with movie clips showing colored disks changing colors, interspersed with short resting-state segments. The collected data was later used to derive reference levels in actual training sessions 2–9. In the following 8 training sessions real-time feedback and movie segments were presented alternated and interspersed with short sections of resting-state.