NeuroImage 111 (2015) 1–11

Contents lists available at ScienceDirect

NeuroImage

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

Oscillatory entrainment of the motor cortical network during motor imagery is modulated by the feedback modality

Mathias Vukelić, Alireza Gharabaghi *

Division of Functional and Restorative Neurosurgery & Division of Translational Neurosurgery, Department of Neurosurgery, Eberhard Karls University Tuebingen, Germany
Neuroprosthetics Research Group, Werner Reichardt Centre for Integrative Neuroscience, Eberhard Karls University Tuebingen, Germany

ARTICLE INFO

Article history:
Accepted 30 January 2015
Available online 7 February 2015

Keywords:
Brain self-regulation
Haptic feedback
Proprioceptive feedback
Brain-robot interface
Brain–machine interface
Brain–computer interface
Beta rhythms
Theta rhythms
Functional connectivity
Neurorehabilitation

ABSTRACT

Neurofeedback of self-regulated brain activity in circumscribed cortical regions is used as a novel strategy to facilitate functional restoration following stroke. Basic knowledge about its impact on motor system oscillations and functional connectivity is however scarce. Specifically, a direct comparison between different feedback modalities and their neural signatures is missing.

We assessed a neurofeedback training intervention of modulating β-activity in circumscribed sensorimotor regions by kinesthetic motor imagery (MI). Right-handed healthy participants received two different feedback modalities contingent to their MI-associated brain activity in a cross-over design: (I) visual feedback with a brain–computer interface (BCI) and (II) proprioceptive feedback with a brain–robot interface (BRI) orthosis attached to the right hand. High-density electroencephalography was used to examine the reactivity of the cortical motor system during the training session of each task by studying both local oscillatory power entrainment and distributed functional connectivity.

Both feedback modalities activated a distributed functional connectivity network of coherent oscillations. A significantly higher skill and lower variability of self-controlled sensorimotor β-band modulation could, however, be achieved in the BRI condition. This gain in controlling regional motor oscillations was accompanied by functional coupling of remote β-band and θ-band activity in bilateral fronto-central regions and left parieto-occipital regions, respectively. The functional coupling of coherent θ-band oscillations correlated moreover with the skill of regional β-modulation thus revealing a motor learning related network.

Our findings indicate that proprioceptive feedback is more suitable than visual feedback to entrain the motor network architecture during the interplay between motor imagery and feedback processing thus resulting in better volitional control of regional brain activity.

Published by Elsevier Inc.

Introduction

The acquisition and learning of motor skills are associated with practice (Doyon and Benali, 2005; Halsband and Lange, 2006). When physical practice is not possible, e.g. in patients with lost motor function following brain damage, motor imagery (MI) might be an effective surrogate for physical practice (Boe et al., 2014; Halsband and Lange, 2006) by activating the sensorimotor system without any overt behavior (Gao et al., 2011; Szameitat et al., 2012). This self-regulation of brain activity during MI can be supported by providing visual or proprioceptive feedback about the current user's brain state (Boe et al., 2014; Dobkin, 2004; Gomez-Rodriguez et al., 2011) using brain–computer interfaces (BCIs) or brain–robot interfaces (BRIs), respectively (Birbaumer and Cohen, 2007; Fetz, 2007; Wolpaw, 2007). First studies applying these approaches in stroke rehabilitation are promising (Ang et al., 2011, 2014; Buch et al., 2008, 2012; Gomez-Rodriguez et al., 2011; Prasad et al., 2010; Ramos-Murguialday et al., 2013; Shindo et al., 2011).

For the purpose of restoring lost motor functions, both BCI and BRI approaches aim at the modification of neural activity via operant conditioning, e.g. challenging the patient to attain specific brain states that guide activity-dependent neural plasticity and thus might facilitate motor recovery (Bauer and Gharabaghi, 2015a,b; Daly and Wolpaw, 2008). Oscillations in the β-band (15–30 Hz) over the sensorimotor cortex are particularly suited for this approach (Gharabaghi et al., 2014a,b,c) as they are linked to the natural communication between cortex and peripheral muscular activity (Davis et al., 2012; Kilavik et al., 2013; Riddle and Baker, 2005; Witham et al., 2011), and reflect sensorimotor control (Brittain et al., 2014), motor learning (Herrojo Ruiz et al., 2014; Pollok et al., 2014), corticospinal excitability (Takemi et al., 2013a,b), and the extent of functional impairment after stroke (Rossiter et al., 2014).

* Corresponding author at: Division of Functional and Restorative Neurosurgery & Division of Translational Neurosurgery, Department of Neurosurgery, Eberhard Karls University, Otfried-Mueller-Str. 45, 72076 Tuebingen, Germany. Fax: +49 7071 29 25104.
E-mail addresses: mathias.vukelic@cin.uni-tuebingen.de (M. Vukelić), alireza.gharabaghi@uni-tuebingen.de (A. Gharabaghi).

http://dx.doi.org/10.1016/j.neuroimage.2015.01.058
1053-8119/Published by Elsevier Inc.

Recent studies showed that providing visual feedback of MI-associated β-oscillations with a BCI increased the laterality at targeted brain regions (Boe et al., 2014) and the movement-associated desynchronization of the targeted β-frequency band (Bai et al., 2014). Proprioceptive feedback of MI-associated β-oscillations with a BRI facilitated decoding of MI induced brain states (Gomez-Rodriguez et al., 2011), activated a distributed cortical network (Vukelić et al., 2014) and bridged the gap between the abilities and cortical networks of motor imagery and motor execution (Bauer et al., 2015). A direct comparison of these two feedback modalities and their neural oscillatory signatures, particularly with regard to the skill for regional self-regulation of β-oscillations and the engagement of distributed functional cortical networks, is however still missing.

We therefore assessed sensorimotor β-activity modulation in participants who received two different feedback modalities in a cross-over design: (I) visual feedback with a BCI and (II) proprioceptive feedback with a BRI. During each session we examined the MI related cortical patterns with high-density electroencephalography (EEG) and functional connectivity analysis. We hypothesized that closing the sensorimotor loop with a BRI would be superior to BCI with visual feedback in supporting self-regulation of β-activity and that this improvement would be mediated by a distinct cortical network resembling the natural activation during overt movement.

Material and methods

Subjects

Eleven right handed healthy volunteers (mean age = 25.83 ± 3.1 years, 4 female), assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), were recruited for this experiment. Participants gave their written informed consent before participation and received monetary compensation. The study protocol was approved by the local ethics committee.

Data acquisition

All participants were comfortably seated upright in a chair. High resolution scalp EEG potentials were recorded (BrainAmp, Brainproducts GmbH, Germany) from 128 positions according to the extended international 10-05 system, with Ag/AgCl electrodes (actiCAP, Brainproducts GmbH, Germany). The left mastoid was used as common reference and EEG was grounded to AFz. All impedances were kept below 20 kΩ at the onset of each session. EEG data was digitized at 1 kHz, high-pass filtered with a time constant of 10 s, transmitted to the BCI2000 software (Schalk et al., 2004) for online processing and stored for off-line analysis.

Experimental paradigm and classification procedure

Fig. 1 indicates an overview of the time course of the experimental paradigm. Each participant was exposed to two MI-associated neurofeedback training sessions in a cross-over design. The sessions were randomized across participants. Each session consisted of three runs lasting 4 min with each run consisting of sixteen trials. Every trial consisted of a cued task design with different task epochs. Each trial was initiated by a preparatory epoch, lasting for 2 s, followed by a MI epoch, lasting for 6 s, and completed by a rest period lasting for 6 s. During each trial, the regional oscillatory activity of the preceding 500 ms was estimated every 40 ms using an autoregressive model based on the Burg Algorithm with a model order of 32 (McFarland and Wolpaw, 2008). Participants were instructed to perform kinesthetic MI (Neuper et al., 2005) of right-hand opening, thus resulting in event-related desynchronization of β-oscillations (β-ERD) over contralateral sensorimotor electrodes (FC3, C3, and CP3) which were used for online classification. We applied an adaptive linear classifier to decode the β-ERD during the MI epoch relative to the average power of the rest and preparation phases of the last 15 s (Gharabaghi et al., 2014a; Vukelić et al., 2014). Hence, during each session we used 9 features for our linear classification consisting of 2-Hz frequency bins (16–22 Hz) and three electrodes overlying sensorimotor areas contralateral to the movement imagination (FC3, C3, and CP3). When a sufficient predefined (see below) level of positively classified β-ERD (five consecutive 40 ms epochs) was reached participants were rewarded with contingent feedback which was either visual via a BCI (one session, lasting 12 min) or proprioceptive via a BRI (one session, lasting 12 min).

To account for different abilities of β-band modulation, prior to the experiment one calibration run was performed, i.e. detecting the strongest individual β-ERD of each participant. This calibration run was done separately for MI + proprioceptive feedback and MI + visual feedback. From each calibration run three threshold values were defined representing different difficulty levels, i.e. the 50% (low difficulty), 30% (moderate difficulty), or 10% (high difficulty) of the strongest, subject-specific β-ERD level, respectively. In the following experimental runs, feedback was only provided when subjects reached either 50% (first run), 30% (second run), or 10% (third run) of their strongest β-ERD. Thereby, the difficulty level increased subsequently throughout the session keeping the participants in the deliberative phase of skill acquisition with high demands for volitional brain modulation. Thus, this study addressed the cortical physiology rather *during* the task than a classical pre/post comparison. During both sessions the participants were instructed to perform no movements to minimize the influence of muscular activity. This was ensured by online monitoring of bilateral forearm muscle activity of the Flexor Carpi Radialis (FCR) and Extensor Carpi Radialis (ECR) muscles, which was further visually inspected offline. Hence, all activities larger than 50 μV were discarded. This was necessary in less than 1% of all trials.

Control of a brain –robot interface (MI + proprioceptive feedback)

During the BRI feedback session the finger tips of the subject were attached to a hand orthosis (Amadeo® system, Tyromotion GmbH, Austria). This orthosis provided closed-loop feedback by opening the hand contingent to volitional modulation of regional sensorimotor β-oscillations as described previously (Gharabaghi et al., 2014a; Vukelić et al., 2014). Subjects were instructed to watch the robotic hand

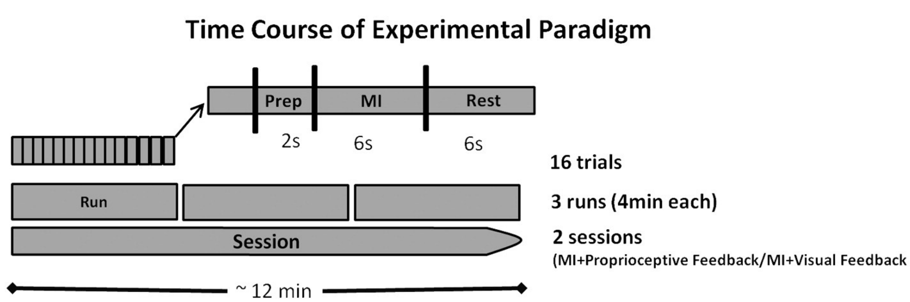

Fig. 1. Experimental paradigm. Time course of the experimental paradigm with two randomized neurofeedback sessions, i.e. proprioceptive feedback and visual feedback.