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Near-infrared spectroscopy based neurofeedback training increases specific motor imagery related cortical activation compared to sham feedback

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ABSTRACT

In the present study we implemented a real-time feedback system based on multichannel near-infrared spectroscopy (NIRS). Prior studies indicated that NIRS-based neurofeedback can enhance motor imagery related cortical activation. To specify these prior results and to confirm the efficacy of NIRS-based neurofeedback, we examined changes in blood oxygenation level collected in eight training sessions. One group got real feedback about their own brain activity ($N = 9$) and one group saw a playback of another person's feedback recording ($N = 8$). All participants performed motor imagery of a right hand movement. Real neurofeedback induced specific and focused brain activation over left motor areas. This focal brain activation became even more specific over the eight training sessions. In contrast, sham feedback led to diffuse brain activation patterns over the whole cortex. These findings can be useful when training patients with focal brain lesions to increase activity of specific brain areas for rehabilitation purpose.

1. Introduction

The ability of an individual to exhibit voluntary control over one's own brain activation is a fascinating research area that has many new potential opportunities for rehabilitation and therapy applications. For instance, disabled or paralyzed people can learn to control a computer, prosthesis or a wheelchair without muscular activity, neurologic patients can learn to increase activity in damaged brain areas or to regulate their own brain activation and achieve cognitive improvements (Coben & Evans, 2010; Kübler & Kotchoubey, 2007; Kübler et al., 2005; Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002). Well established brain imaging methods such as electroencephalography (EEG) or functional magnetic resonance imaging (fMRI) are typically used for assessing brain activation and providing participants feedback about these signals. The aim of the present study is to investigate if near-infrared spectroscopy (NIRS), a relatively new neuroimaging method compared to EEG and fMRI, can be used for such applications as well.

Theory of neurofeedback (NF) often refers to operant conditioning of brain activation, in most cases concerning electroencephalographic (EEG) rhythms (Kropotov, 2009). There are a huge number of NF studies using EEG as feedback signal because of its high temporal resolution and usability (Coben & Evans, 2010; Coben, Linden, & Myers, 2010; Gruzelier & Egner, 2005; Kropotov, 2009; Niv, 2013; Vernon, 2005). EEG based NF applications turned out to be useful in clinical practice since voluntary modulation of specific EEG frequency bands usually leads to improvements in cognition and behavior (Coben & Evans, 2010). The number of EEG based NF studies is still constantly rising. However, EEG parameters are not the only physiological parameters that reflect functioning of the brain. Hemodynamic/metabolic activity of the brain measured by functional magnetic resonance imaging (fMRI) or near-infrared spectroscopy (NIRS) can be effectively used as NF signal as well (Yoo, Lee, O'Leary, Panych, & Jolesz, 2008). These parameters can be fed back to the participants and, consequently, can be used for voluntary control of brain functions (Kropotov, 2009).

Recently, a number of studies focused on online detection of hemodynamic correlates of neural activity using fMRI and providing participants with feedback about their hemodynamic responses (Matthews, Pearlmutter, Wards, Soraghan, & Markham, 2008; Sitaram, Caria, et al., 2007; Weiskopf, 2012). The fMRI signal can be used as a control signal for a brain-computer interface (BCI)

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or to provide neurofeedback to the participants (LaConte, 2011). While in both BCI and NF the participant's brain signals are directly displayed to the participant in real-time, these applications differ conceptually. BCI can be seen as a direct communication pathway between a human brain and an external device such as a wheelchair, a computer or prosthesis (Kropotov, 2009). In BCI, the recorded brain signal is translated in real-time into commands that operate a computer display or other device (Wolpaw et al., 2002). In neurofeedback applications, the feedback parameters are used for self-regulation of the brain (Kropotov, 2009). In neurofeedback experiments participants learn to control brain activity by contingent feedback of measures of the brain activity (Weiskopf, 2012). A comprehensive review of studies using fMRI for BCI or neurofeedback is provided by Weiskopf (2012) and LaConte (2011). There is evidence that participants can learn enhanced voluntary control over task-specific activation in the somatomotor cortex by imagery of hand or foot movements and getting visual feedback about their level of activation in the somatomotor cortex by using real-time functional magnetic resonance imaging (rtfMRI) (Bray, Shimojo, & O'Doherty, 2007; deCharms et al., 2004; Yoo et al., 2004). This enhancement takes place when rtfMRI-based training is provided but cannot be observed in control groups receiving similar training without rtfMRI information (deCharms et al., 2004). Furthermore, Bray, Shimojo, and O'Doherty (2007) demonstrated that after rtfMRI-based NF training, in which participants imagined movements to control neural activity in motor areas, the performance in a reaction-time task increased compared to the performance before the NF training, when the physical response engages regions similar to those activated by the learned neural response. Hence, these findings provide evidence that fMRI-based NF might be useful in therapies for patients who have suffered stroke damage to the motor system (Bray et al., 2007).

Although there is empirical evidence that rtfMRI can be used successfully for BCI or NF applications with high spatial resolution and whole brain coverage, one has to add that fMRI measurements are associated with some disadvantages as well (Weiskopf, 2012). For instance, some participants experience some discomfort while lying in the MRI scanner because of the noise and the narrow scanner. Additionally, fMRI is an expensive neuroimaging method, locally bounded to the installation site and restricted in study design due to the limitation of the participant's free moving. To reduce costs and increase accessibility and portability near-infrared spectroscopy (NIRS) may represent a good and adequate alternative to measure the blood oxygenation level dependent (BOLD) effect in cortical areas (Weiskopf, 2012). NIRS is a non-invasive optical neuroimaging method technique that measures concentration changes of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) in the cerebral vessels based on their different absorption spectra for light in the near-infrared range (Villringer & Chance, 1997). The typical hemodynamic response to mental activation is the measurement basis of NIRS, such as for fMRI. When a specific brain area is activated, neural metabolism is supported through a localized vascular response that causes an influx of oxygen-rich blood to the active area and its surrounding tissue. Consequently, this leads to an increase in oxy-hemoglobin (oxy-Hb) and a decrease in deoxy-hemoglobin (deoxy-Hb) in the active brain area (Matthews et al., 2008). Compared to EEG, the montage of the NIRS optodes is very fast. Repeated NIRS measurements are also more comfortable for participants as no abrasive gel is needed that may lead to skin irritations. Compared to fMRI, it has low costs, is more flexible and portable. Furthermore, NIRS has a higher temporal resolution than most commonly used fMRI scanners (Huppert, Hoge, Diamond, Franceschini, & Boas, 2006; Sitaram, Caria, & Birbaumer, 2009) and also wireless and portable instruments are available (Muehlemann, Haensse, & Wolf, 2008; Sitaram et al., 2009). Compared with both fMRI and EEG, NIRS has a lower sensitivity to motion-artifacts and can accommodate a higher degree of movement (Lloyd-Fox, Blasi, & Elwell, 2010; Nambu et al., 2009), allowing measurements of brain activation also in natural and realistic environments.

Because of the above mentioned advantages of NIRS over fMRI and EEG, there is upcoming research interest in NIRS-based brain–computer interfaces and neurofeedback applications. A few studies investigated if the NIRS signal can be used as control signal for BCI purposes. These studies successfully used different mental strategies, such as motor imagery or mental arithmetic, to control a NIRS-based BCI. When classifying the NIRS signal, relative high classification accuracies can be achieved, which are comparable with classification accuracies of EEG based BCIs (Ang et al., 2010; Bauernfeind, Scherer, Pfurtscheller, & Neuper, 2011; Coyle, Ward, & Markham, 2007; Fazli et al., 2012; Holper & Wolf, 2011; Limongi, Di Sante, Ferrari, & Quaresima, 2009; Matsuyama & Otake, 2009; Min, Marzelli, & Yoo, 2010; Power, Kushki, & Chau, 2012; Sitaram, Zhang, et al., 2007; Sitaram et al., 2009; Soraghan et al., 2008). Hence, NIRS promises to be a potent device for future BCIs because of its flexibility of use, portability, metabolic specificity, high sensitivity in detecting small substance concentrations and affordability (Min et al., 2010). Nevertheless, one has to add that the NIRS signal (and the fMRI signal) has a number of inherent delays. The biologically inherent hemodynamic response delay requires about 2 s to arise and about 4–6 s to reach its peak amplitude after neural activation (Cui, Bray, Reiss, & Tell, 2010; deCharms et al., 2004). Hence, there is a delay between the beginning of neural activation and the sensory feedback provided to participants, which has to be explained to participants before the NF/BCI training.

Compared to growing body of NIRS-based BCI research, where NIRS parameters are used to control external devices, NIRS-based NF studies are rare. Mihara et al. (2012) investigated the feasibility and efficacy of a real-time neurofeedback system based on NIRS (Mihara et al., 2012). They found that participants who got real feedback about changes in blood oxygenation level during a motor imagery task showed significant greater activation in relevant cortical brain areas than participants who got sham feedback. Hence, this study shows for the first time that participants can learn to voluntarily control their hemodynamic response due to NF training and indicates the feasibility and potential effectiveness of a NIRS-based real-time neurofeedback system (Mihara et al., 2012).

The present study aimed to specify and expand these prior results of Mihara et al. (2012), to confirm the efficacy of NIRS-based neurofeedback training, and to investigate NF-related changes in brain oxygenation over a larger number of training sessions. Therefore, changes in blood oxygenation level due to a repeated NIRS neurofeedback training were examined and compared between a real feedback group and a sham feedback group. Participants were instructed to imagine a right hand movement to control the vertical position of a ball displayed on a computer screen. If one can learn to voluntarily control their hemodynamic response due to NIRS-based NF training, participants getting real feedback about their own brain activation should show a specific activation over left motor areas during right hand motor imagery, whereas the sham feedback group that gets no real feedback should show a diffuse brain activation. Changes in cortical activation during motor imagery were correlated with participants' subjective estimation of their motor imagery ability and compared between the two feedback groups. We hypothesize that there should be a correlation between the participants' ability to imagine movements and changes in blood oxygenation level during motor imagery in the real feedback group, whereas in the sham feedback group no significant correlations are expected. Additionally, we wanted to examine whether the enhanced cortical activation associated with motor imagery becomes even more specific over repeated NF training sessions in the real feedback group compared to the sham feedback group.