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Holper Lisa[1], Wolf Martin[1]

[1] Biomedical Optics Research Laboratory (BORL), Clinic of Neonatology, University Hospital Zurich, Switzerland

Corresponding author:

Lisa Holper, Dr. med.

Biomedical Optics Research Laboratory (BORL)

Clinic of Neonatology

University Hospital Zurich

Frauenklinikstrasse 10

8091 Zurich

Switzerland

Phone: +41 (0)44 255 97 92

Fax: +41 (0)44 255 44 42

Email: holper@ini.phys.ethz.ch

Abstract

The objective of this study was to describe brain oxygenation patterns during motor imagery (MI) in response to feedback using functional near-infrared spectroscopy (fNIRS). fNIRS was recorded over the primary motor cortex in 15 healthy subjects using a right hand motor task during four fake feedback conditions: MI without Feedback (MI(0)), MI with positive (MI(+)) and negative Feedback (MI(-)) and during actual movement execution (ME) as control task. Behavioral data were collected using the Edinburgh Handedness Inventory (EHI) and The Kinesthetic and Visual Imagery Questionnaire (KVIQ-10).

We observed inter-condition differences and inter-subject variability in signal amplitude with larger O_2Hb concentration changes both in response to MI(+) (0.154 ± 0.067 µmol/l) and MI(-) (0.129 ± 0.074 µmol/l) as compared to MI(0) (0.109 ± 0.024 µmol/l) and ME (0.210 ± 0.013 µmol/l).

We present fNIRS data of MI performance in response to different feedback conditions indicating that there exist distinct oxygenation patterns. These data may contribute to the development of fNIRS controlled feedback systems.

Keywords: functional near-infrared spectroscopy (fNIRS), motor imagery, feedback, Edinburgh Handedness Inventory (EHI), Kinesthetic and Visual Imagery Questionnaire (KVIQ-10)

1 Introduction

1.1 Motor imagery (MI)

MI is a term introduced by cognitive neuroscientists to describe mental rehearsal of voluntary movement, a cognitive state which can be experienced by most people (Annett 1995; Porro, et al. 1996). The so called 'simulation hypothesis' (Jeannerod 1994) characterizes MI as imagining of motor actions defined as an active process during which a specific action is internally reproduced without overt movement execution (Decety and Grèzes 1999; Decety and Ingvar 1990; Solodkin, et al. 2004). The hypothesis suggests that the neural networks activated during MI performance share overlapping brain areas with those activated during overt movement execution, thought to be located in primary motor, premotor and parietal cortices (Lotze, et al. 1999). Activation of these brain areas following MI may therefore facilitate subsequent movement execution by directly matching the imagined action onto the internal simulation of that action (Rizzolatti, et al. 1999). Such facilitation could contribute to various forms of motor learning (e.g., observational learning as observed in childhood), professional motor training (e.g., mental training used by athletes (Holmes and Calmels 2008) or musicians (Lotze and Halsband 2006) attempting to improve performance) and therapeutically relearning of impaired motor function as an essential role in neurorehabilitation (e.g. following cerebral stroke (De Vries and Mulder 2007; Dickstein, et al. 2004; Ertelt, et al. 2007; Malouin, et al. 2008; Sharma, et al. 2006; Weiss, et al. 1994)).

Two types of imagery have been described. MI, also known as kinesthetic motor imagery is thought to produce stronger activation in motor related areas compared to the second type of imagery, known as visual imagery (Neuper, et al. 2005). Whereas MI is supposed to involve kinesthetic experiences using first-person imagery, visual imagery uses the third-person perspective. Training effects of motor skills such as coordination and timing are thought to be more effective using first- compared to third-person imagery, indicating larger training benefit for kinesthetic motor imagery than visual imagery (Féry 2003).

Several questionnaires have been developed to assess individual imagery ability of both types to select subjects able to engage and potentially benefit from imagery training. One example is the Kinesthetic and Visual Imagery Questionnaire (KVIQ) (Malouin, et al. 2007) that evaluates imagery ability assessing the clarity of the image (visual imagery scale (VIS)) and the intensity of the sensations (kinesthetic imagery scale (KIS)). As the questionnaire was designed for use in motorically impaired individuals, it involves movements that can be performed more easily as compared by other imagery questionnaires such as the Movement Imagery Questionnaire (MIQ) (Hall and Martin 1997) and the Vividness of Mental Imagery Questionnaire (VMIQ) (Isaac, et al. 1986).

1.2 Motor imagery measured by fNIRS

While MI has been extensively studied using traditional neuroimaging methods such as functional magnetic resonance imaging (fMRI) (Johnson-Frey 2004; Sharma, et al. 2006) and electroencephalography (EEG) (Neuper, et al. 2006a), there are only few data using functional near-infrared (NIR) spectroscopy (fNIRS). fNIRS is a comparably young neuroimaging method (Jöbsis 1977) that uses optical signals to measure localized cortical brain activity. The method is based on neurovascular coupling, which exploits the relationship between metabolic activity due to neural processing and the oxygenation and Hb concentration in blood vessels. Utilizing this tight coupling between neuronal activity and regional cerebral blood flow, fNIRS measures regional hemodynamic changes of oxy-hemoglobin (O_2Hb) and deoxy-hemoglobin (HHb) associated with cortical activation (Villringer and Dirnagl 1995). During the last 30 years, optical NIR technology has been shown to be a reliable tool for functional neuroimaging of the human brain (Wolf, et al. 2007).

Previous fNIRS studies measuring cortical oxygenation during MI confirmed activation in the well-known areas located in primary, premotor and supplementary motor areas. Most studies were performed in healthy subjects (Cooper, et al. 2006; Coyle, et al. 2007; Coyle, et al. 2004; Miyai, et al. 2001; Sitaram, et al. 2007; Wriessnegger, et al. 2008) (except a case study in a patient suffering from amyotrophic lateral sclerosis (ALS) (Fuchino, et al. 2008)) and used

imagery of hand movements (except one that used imagery of gait (Miyai, et al. 2001)). Unfortunately, some studies failed to report the type of imagery and the specific hand motor task performed. Further, only few studies included a control condition, such as overt movement execution according to the simulation hypothesis (Miyai, et al. 2001; Sitaram, et al. 2007). While some of these studies focused on various aspects of MI performance (Cooper, et al. 2006; Fuchino, et al. 2008; Miyai, et al. 2001; Wriessnegger, et al. 2008), others focused on the context of brain computer interfaces (BCIs) aimed to be developed as training tools in neurorehabilitation (Coyle, et al. 2007; Coyle, et al. 2004; Sitaram, et al. 2007).

1.3 Feedback systems

One key to successful motor training is feedback-based learning, which refers to our ability to use performance feedback to adapt subsequent behavior. Both positive and negative feedback are thought to be important for improving performance, signaling continuation and/or adjustment of current behavior (van Duijvenvoorde, et al. 2008).

Recent applications of feedback focus on the development of brain computer interfaces (BCIs), training systems that allow individuals to control devices in real time. A BCI does not rely on motor execution, i.e. muscular activity, but is rather controlled through brain signals of mental operations such as MI. An essential precondition for controlling BCIs within a training setting is that users acquire conscious control over their brain activity by learning self-regulation of localized brain regions. One approach to control brain activity is to concentrate on a specific mental task, e.g. the imagery of hand movements. In this approach, feedback is used to let subjects learn the production of easily detectable signal pattern of their own brain signals.

Different brain signals have been used to control a BCI, such as fMRI and EEG ((Fetz 2007; Neuper, et al. 2006a); for review see (Kübler and Kotchoubey 2008; Patil and Turner 2008)). However, although fMRI provides data on hemodynamic brain activation with good spatial resolution, it requires cumbersome equipment, is not portable, and is sensitive to interference from other equipment. EEG provides electrical brain signals with high temporal resolution and

can be portable could therefore be an ideal combination with NIRS offering information both about the neural and hemodynamic brain changes.

New approaches using fNIRS have been evaluated to establish novel signal acquisition tools for BCIs ((Coyle, et al. 2007; Ranganatha, et al. 2007; Soraghan, et al. 2006); for review see (Sitaram, et al. 2009)). Compared to fMRI and EEG, fNIRS offers advantages besides being safe, non-ionizing, non-invasive. The technique can be simply measured by placing small sensors on the scalp, even using wireless or portable instruments (Muehlemann, et al. 2008) and does not require strict constraints of the subject's body or head. It is also relatively inexpensive when compared to either EEG or fMRI. Therefore, it enables the investigation of brain activation in natural, realistic, everyday environments, or in clinical settings. Although the signal is slower than available using EEG (and similar to fMRI), fNIRS systems are ideally suited to provide online feedback.

1.4 Aims

The present study aims to contribute within long term to the development of NIRS controlled feedback system. We therefore expanded previous fNIRS studies using a novel feedback approach. Cortical signals were recorded during MI performance of a hand motor task in response to four fake feedback conditions: MI without Feedback MI(0), MI with positive MI(+) and negative Feedback MI(-); as control condition overt movement execution (ME) was used. Using this approach the objective of this study was to test whether different feedback conditions following MI performance result in different brain oxygenation patterns.

Based on the known properties of the simulation hypothesis, we not only hypothesized to observe stronger oxygenation changes during condition ME compared to the MI conditions (because the related neural network is most active when subjects are performing movements), but also a higher oxygenation changes in condition MI(+) and MI(-) relative to MI(0) (because the activation in the related neural network may represent the encouragement versus discouragement evoked by the feedback). We aimed to describe the basic common pattern of those oxygenation changes measured by fNIRS.

2 Materials and Methods

2.1 Subjects

Subjects were recruited via notice at the University of Zurich and ETH Zurich. Exclusion criteria were any history of visual, neurological or psychiatric disorder or any current medication. All subjects gave informed consent after the study has been explained to them. All subjects had normal or corrected-to-normal vision. The study was approved by the ethics committee of the canton of Zurich and was in accordance with the latest version of the Helsinki declaration.

2.2 Experimental design

Experiments were conducted in a quiet room at the University Hospital Zurich. Each subject was measured in one session. Subjects were asked to sit at a table, place their hands on the table and face a computer screen at a distance of approx. 70 cm.

2.2.1 Behavioral measures

Prior to recording, subjects completed two questionnaires. The Edinburgh Handedness Inventory (EHI) (Oldfield 1971) was used to assess hand dominance selecting right-handed subjects. The Kinesthetic and Visual Imagery Questionnaire (KVIQ-10, short version) (Malouin, et al. 2007) was used to select subjects with good imagery abilities (global score > 2.5). The KVIQ-10 consists of 10 items (each side 5 simple movements) measured separately on a kinesthetic (KIS) and visual imagery scale (VIS): forward shoulder flexion, thumb to finger tips, forward trunk flexion, hip abduction and foot tapping. Subjects were recruited on the basis of their global KVIQ-10 score. The assessment further allowed subjects to familiarize with MI performance by using motor tasks different from those later used in the study.

2.2.2 Conditions

The experimental design comprised four conditions conducted in a block design (Figure 1). Each condition lasted 10 minutes consisting of 15 trials with stimulation periods (20 sec) alternated with rest periods (20 sec). Total measurement length was 40 minutes. Subjects were

instructed to perform all tasks as precise as possible while avoiding errors or task-unrelated movements, documented by the experimenter. Between conditions, subjects were encouraged to take short breaks to prevent fatigue. Previous results showed that the application of pacing stimuli results in higher motor activation related to finger-tapping tasks than without (Witt, et al. 2008). Therefore, all conditions were paced by visual stimuli generated by the software Presentation® (Neurobehavioral systems, Albany, USA) center of the screen.

*Condition **ME** (Movement Execution):* Subjects were asked to perform a right hand finger-tapping task as used in various fMRI studies investigating hand motor function (Cao, et al. 1998; Chollet, et al. 1991; Horenstein, et al. 2009; Seitz, et al. 1998; Weiller, et al. 1993). Finger-tapping consisted of a predefined sequence by pressing five buttons on a keyboard using all five fingers (once each): thumb, middle, pinky, index, ring finger, i.e. “1-3-5-2-4”. The sequence was repeated in a frequency of approx. 2 Hz, resulting in approx. eight sequences for each stimulation period (20 sec). During rest periods subjects were asked to place the right hand next to the keyboard while avoiding any muscle tension. The stimulus ‘GO’ requested subjects to start the task at the beginning of the stimulation period, the stimulus ‘STOP’ requested subjects to stop the task at the beginning of the rest period which was then replaced by a fixation cross until the start of the next trial. Prior to recording, subjects were trained to use the keyboard. Behavioural performance of the correct order of finger-tapping sequences (target keys) was recorded using a wireless numerical keyboard (Logitech® Cordless Number Pad) and stored in the log files of Presentation® (Neurobehavioral systems, Albany, USA) for further analysis.

*Condition **MI(0)** (Motor Imagery without Feedback):* Subjects were asked to perform MI by imagining the kinesthetic experience of the same task executed in condition ME in a first-person perspective, while avoiding any muscle tension. The same visual pacing stimuli were used. Subjects received the instruction: ‘Your job is to try to form a good mental image of the finger-tapping task. You must feel yourself performing this task and experience all of the sensations involved in the actual movement’. They were reminded to perform equal numbers of imagined

finger-tapping using the same tapping frequency (2 Hz) as in condition ME. During rest periods subjects were asked to imaging placing their right hand next to the keyboard.

*Condition **MI(+)** (Motor Imagery with positive Feedback):* Subjects were asked to perform the same task as in condition MI(0). In addition, feedback was given at the end of each stimulation period (adapted from (Bischoff-Grethe, et al. 2009)) in a random order: In 5 trials (33%) positive feedback was given represented by the stimulus 'CORRECT'; in the remaining 10 trials (66%) no feedback was given represented by the stimulus 'UNKNOWN'. Stimuli were then replaced by a fixation cross until the start of the next trial. Feedback stimuli were not related to subjects' actual MI performance, a fact that was not known to the subjects, and were purposely very short to allow subjects not to lose the ability to concentrate. In addition to the instruction from condition MI(0), subjects were told: 'Your goal is to gain as much positive feedback as possible. The better you perform the more positive feedback you gain'.

*Condition **MI(-)** (Motor Imagery with negative Feedback):* Subjects were asked to perform the same task as in condition MI(+). The only difference was that the feedback ratio was changed to 33% negative feedback represented by the stimulus 'INCORRECT' and 66% no feedback.

The order of the tasks required all subjects first to perform condition ME followed by conditions MI(0), MI(+) and MI(-) in a pseudo-randomized order (Easy Randomizer, Version 4.1. by (Bricker)) to, at least partially, avoid ordering effects.

2.3 Instrumentation

For review and discussion of existing NIRS methods and systems, see (Boas, et al. 2004; Hoshi 2003; Obrig and Villringer 2003; Strangman, et al. 2002; Wolf, et al. 2007).

The multi-channel CW instrument, the MCP-II, used in our study (Haensse, et al. 2005) consists of a sensor and a data acquisition unit. The sensor incorporates emission and detection of NIR light using four light sources and four detectors covering an area of 25 mm by 37.5 mm (Figure 2). Each light source comprises light emitting diodes (LED) with wavelengths of 750nm, 800nm and 875nm. The LEDs are time multiplexed; i.e. only one source is on at a time. Two detectors

(PIN photodiodes) can measure the light of each LED simultaneously. O_2Hb and HHb concentration changes are measured in 10 channels simultaneously.

The light sources and detectors are mounted onto a rigid-flexible printed circuit board (PCB) which is cast in a highly flexible cover made of medical grade silicone rubber. The flexibility of the sensor allows it to be aligned to curved body surfaces such as the head. Even though the source-detector distance is fixed, the flexibility of the sensor may imply that the exact source-detector distance varies by a few millimetres. The sensor is connected to the data acquisition unit, which transfers data to a laptop to store for further analysis and display.

The data acquisition unit of the MCP-II allows the simultaneous measurement of up to 48 channels with a sampling rate of 100 Hz and low noise. According to in vitro studies by (Haensse, et al. 2005), for the current protocol the instrumental detection limit for a change in μa is <0.00002 [1/cm], which corresponds to a concentration change of 0.005μM.

The fNIRS sensor was placed on the subject's head covering C3 according to the international 10-20 system (Jaspers 1958). With the compact sensor of 3.75 mm length and 25 mm width, we assumed covering cortical areas including primary motor cortex. The subject's head was then covered with a custom-made cap to adjust and fixate the sensor. Hairs under the sensor were carefully brushed away to avoid problems with signal detraction.

3 Data Analysis

3.1 Behavioral measures

Data analysis was performed using SPSS® (Version 16.0). Descriptive statistics were calculated for the EHI (mean laterality quotient (LQ); mean deciles level) and the KVIQ-10 (mean global scores; separate scores for KIS and VIS).

In order to evaluate a possible relationship between imagery ability and fNIRS activation patterns, non-parametric Spearman rank order correlation coefficients were computed between the KVIQ-10 scores and the hemodynamic response parameters (O_2Hb, HHb). This analysis

was also performed by grouping subjects into groups with low versus high imagery ability as documented by the KVIQ-10; for the latter, three different cut-off global scores were tested (global score 3, 3.5 and 4).

Tapping performance in condition ME was analyzed as described by (Horenstein, et al. 2009): Total number of finger taps and error rates were calculated for each individual subject by counting incorrect sequences. An error was defined as any finger tap occurring outside the prescribed sequence and the error rate was defined as the (total number of errors)/(total number of finger taps).

3.2 fNIRS measurements

A customized algorithm implemented in MATLAB® (Version R2008a) performed the signal processing and the transformation of the raw data into concentration changes of O_2Hb and HHb. fNIRS raw data contain the intensities of NIR light for all light-source/detector/wavelength combinations in use, intensities of background light and event markers. Based on the raw data, the given geometry of the sensor, and the application of the modified Beer-Lambert law, concentration changes of O_2Hb and HHb were calculated (Haensse, et al. 2005). The differential path length factor (DPF) was set to 7.5, 7.25 and 7.0 at 750nm, 800nm and 875nm (Zhao, et al. 2002).

Movement artifacts were detected using a variance filter which calculated the sample wise absolute difference (SWAD) between low-pass filtered (fc=0.1Hz) data and raw data, determined the variance of SWAD and rendered sample-points as invalid which exceed 6 times the median of SWAD. Data were declared invalid when a concentration change of at least 80µmol/l appears within a 0.5s interval. Before data were used for further analysis, it was smoothed by a 501 points, 1st order Savitzky-Golay filter.

Data were then transferred to SPSS® (Version 16.0). From the resulting signals, the O_2Hb and HHb concentrations during the last 10 seconds of each stimulation period were averaged and compared to the concentrations during the last 10 seconds of each rest period. This method of using only the last 10 sec of each period was chosen to concentrate the analysis on the

temporal intervals where the concentration of oxygenation changes can be considered as stabilized. Whereas at the beginning of each period the concentration of oxygenation is in the transition phase, i.e. increasing or decreasing from the rest to the stimulation period.

Over all subjects the statistical significance of intra-condition differences of the average change in O_2Hb and HHb concentrations between rest and stimulation periods were calculated using the paired Wilcoxon sign rank test. Intra-subject variability between O_2Hb and HHb amplitudes were calculated by means of the standard deviation (SD). Inter-condition statistical significance between the average differences of O_2Hb and HHb concentrations between rest and stimulation periods between the four conditions were assessed using one-way ANOVA. Significance alpha-value was set to 0.05, and the Bonferroni correction was used for ANOVA.

4 Results

4.1 Behavioral measures

15 healthy subjects (six males, mean age 29 year, range 23 – 38 years) were included in the study. Table 1 showed the behavioral measures. All subjects were right-handed with a mean LQ of 89.7 (range 77 – 100) and a mean deciles level of 7.1 (range 5 – 10). The mean global KVIQ-10 score over all subjects was 3.37 (range 2.2-4.4); mean separate scores for VIS (2.91) were slightly lower as compared to KIS (3.83). Scores for each item for the VIS were: 2.60 for 'Forward shoulder flexion', 2.87 for 'Thumb to finger tips', 3.20 for 'Forward trunk flexion', 3.00 for 'Hip abduction' and 2.87 for 'Foot tapping'. Scores for the KIS were: 3.67 for 'Forward shoulder flexion', 3.73 for 'Thumb to finger tips', 4.00 for 'Forward trunk flexion', 3.87 for 'Hip abduction' and 3.87 for 'Foot tapping'. Tapping performance of the right hand over all subjects in condition ME revealed mean total taps of 853 ± 265 and a mean error rate of 0.04 ± 0.05. There were no significant correlations between these parameters, the KVIQ-10 individual and group scores and/or the O_2Hb and HHb concentration changes.

4.2 fNIRS measurements

Only channels showing the typical activation pattern, i.e. the combined occurrence of significant increase of O_2Hb accompanied by significant decrease of HHb concentration, were used for analysis. Based on the occurrence of the typical activation patterns, inter-condition differences were observed between the amplitudes of O_2Hb and HHb concentration changes.

Over all subjects, the amplitudes of O_2Hb concentration changes were up to three times higher as compared to HHb concentration changes (Table 2). Maximal O_2Hb amplitudes were observed during condition ME (0.210 µmol/l), followed by condition MI(+) (0.154 µmol/l), MI(-) (0.129 µmol/l) and MI(0) (0.109 µmol/l) (Figure 4). No relationship was found between the HHb concentration changes and those of O_2Hb, with maximal HHb amplitudes observed during condition MI(0) (-0.102 µmol/l), followed by condition ME (-0.089 µmol/l), MI(-) (-0.054 µmol/l) and MI(+) (-0.045 µmol/l).

A remarkable high degree of inter-subject variability was observed for the O_2Hb amplitudes as calculated by the standard deviation (SD) of the mean oxygenation changes (Table 2). In the four conditions, the mean O_2Hb amplitudes varied most among subjects during MI(+) (SD ± 0.067 µmol/l) and MI(-) (SD ± 0.074 µmol/l) as compared to during ME (SD ± 0.013 µmol/l) and MI(0) (SD ± 0.024 µmol/l).

Using the paired Wilcoxon sign rank test (Table 3), statistical significance of the average change in O_2Hb concentrations between the stimulation and the rest periods were found for condition ME ($p \leq 0.001$), condition MI(0) ($p = 0.014$), condition MI(+) ($p = 0.009$) and condition MI(-) ($p = 0.026$). The average change in HHb concentrations (Table 3) showed significant values for condition ME ($p = 0.028$) and MI(+) ($p = 0.016$). Using ANOVA (Table 3) for O_2Hb amplitudes revealed no significant main effect of condition. Post-hoc tests showed only a significance difference between condition ME and MI(0) ($p = 0.023$). Between the other conditions no statistical significance was revealed, but a trend as described above was observed. The mean HHb amplitudes did not show such a variability, with MI(+) (SD ± 0.012 µmol/l), followed by condition ME (SD ± 0.008 µmol/l), MI(0) (SD ± 0.007 µmol/l) and MI(-) (SD ± 0.005 µmol/l). Using ANOVA for HHb (Table 3) amplitudes revealed significance differences between all

conditions except conditions ME / M(0) and MI(+) / MI(-). No relationship was found between O_2Hb and HHb concentration changes, i.e. there was no evidence that high O_2Hb concentration changes were correlated with high HHb changes or vice versa. Figure 3 shows the distribution of amplitudes between the four conditions indicating inter-subject variability by SD (red lines).

5 Discussion

5.1 Feedback in human performance

Humans use feedback to learn how to perform movements. Feedback learning plays a major role in childhood and also supports relearning of impaired motor function in adults, such as after brain injury. Both require the individual's ability to discriminate between and subsequently adapt motor performance either to positive feedback, indicating that the performance was sufficient, or to negative feedback, indicating that the performance needs to be intensified (Bransford, et al. 1999). It is not surprising therefore, that brain activation patterns change depending on the response to different feedback (Bischoff-Grethe, et al. 2009).

For feedback systems, decoding the neural responses elicited by MI performance may be useful particularly from a rehabilitation perspective. The neurobiology of both feedback control and rehabilitation depends upon learning to modify the efficacy of spared neural ensembles that represent movement through progressive practice with feedback and reward (Dobkin 2007). In neurorehabilitation for (re)learning of impaired motor function, offering immediate feedback about motor performance may enhance training effects (Buch, et al. 2008; Davidson and Wolpert 2005; De Vries and Mulder 2007; Diamond 2001; Neuper, et al. 2009). Through direct comparison between actual and target performance, feedback can support patient's motivation and help therapists in treatment monitoring.

To contribute to the development of fNIRS controlled feedback systems, the present study expanded previous fNIRS studies using a new approach by investigating MI performance in response to fake feedback: no, positive or negative feedback. It was aimed to provide fNIRS data of cortical MI activation pattern that allow for differentiation between these different

feedback stimuli. Our results indicate that there exist distinct MI activation patterns concerning the amplitude of brain oxygenation.

5.2 Feedback on MI may affect behavioral and neural responses

The use of our behavioral MI task was motivated as it has been shown to activate brain areas responsible for processing positive and negative feedback using fMRI (Bischoff-Grethe, et al. 2009). We are aware that our study does not assess all areas involved in feedback processing, and rather aimed to activate those motor-related areas involved in MI performance.

Generally, responses to feedback tasks may be described in a bidirectional manner: positive feedback promotes reinforced behavior (Thut, et al. 1997), whereas negative feedback attenuates that behavior (Ito 2000). In accordance, we observed larger O_2Hb amplitudes in motor-related areas after positive feedback as compared to no feedback, maybe indicating that our subjects enhanced their performance performed after receiving positive feedback. This is supported by the motivational theory of control, i.e. that positive feedback increases success expectations (Carver and Scheier 1981). However, when presenting negative feedback to our subjects, again increased O_2Hb amplitudes compared to without feedback was observed, though smaller than after positive feedback. This may indicate that out task induced performance enhancement in both positive and negative feedback conditions. Our results may therefore not indicate a bidirectional, but a unidirectional behavior.

Bi- versus unidirectional behavior in response to feedback might be a consequence of how subjects are instructed how to respond to a certain feedback task (Bischoff-Grethe, et al. 2009). In both our feedback tasks, subjects were instructed to gain as much positive feedback as possible. Consequently, both in response to positive and negative feedback, subjects were encouraged to intensify their effort in MI performance. It still needs to be determined, which tasks compositions and instructions inducing bi- or unidirectional responses may particularly be valuable for feedback in rehabilitative training where patients would be require not only to enhance their imagery performance but also improve motor performance.

5.3 Movement execution used as control task for MI

Movement execution is often used as control task in BCIs, although it has not been regularly applied in previous fNIRS studies (Cooper, et al. 2006; Coyle, et al. 2004; Miyai, et al. 2001; Sitaram, et al. 2007; Wriessnegger, et al. 2008). Using ME as control task, we confirmed that MI shares overlapping neural structures in the primary motor cortex. In accordance with well-known findings in fMRI and EEG, (Beisteiner, et al. 1995; Buccino, et al. 2006; Filimon, et al. 2007; Grèzes and Decety 2001), we observed inter-condition differences with lower levels in the amplitude during MI tasks compared to ME. This fact may be explained by the simulation hypothesis, i.e. the motor system inhibits overt movements during imagery (Fadiga, et al. 1998; Lotze, et al. 1999; Neuper, et al. 2006b).

5.4 MI performance related to fNIRS signal amplitude

We observed differences in signal amplitude that could provide a basis for differentiating between the activation task MI with lower O_2Hb occurrence and amplitude, compared to the control task ME. Additionally, we detected higher inter-subject variability in O_2Hb amplitudes during MI tasks following positive or negative feedback as compared to without feedback or ME. General reasons for these individual variability may be effects of anatomical variance such as thickness of the skull and cerebrospinal fluid layers (Okada and Delpy 2003a; Okada and Delpy 2003b). However, this does not explain why variability is prominent during MI tasks following positive or negative feedback and low during without feedback or ME. We therefore evaluated the relationship between O_2Hb amplitudes and the individual imagery ability (KVIQ-10 scores), but did not found significant correlations over all subjects. Although, the overall missing correlation between individual and overall KVIQ-10 scores and oxygenation changes in our subjects is in line with a previous study (Wriessnegger, et al. 2008), the selection of our subject might have biased the results as we did not include individuals with very low imagery ability. Further, our subjects had no prior experience in MI, were not specifically trained prior to the experiment and might therefore been rather heterogeneous with respect to their imagery ability. Hence, it needs to be questioned whether the in the questionnaire self-reported imagery ability

may be the appropriate indicator of how well subjects could imagine the specific hand movements in the present experimental procedure. The cognitive processes underlying this procedure may be distinct from the general imagery ability assessed with the KVIQ-10. Generally, the question to which extent a person is able to generate a mental representation of movements is even more relevant in the assessment of individuals following brain injury. Such lesions involving specific cortical areas, e.g. the parietal cortex, may impair certain imagery abilities (Sirigu, et al. 1996), such as overall slowing of imagery processes resulting in modified temporal characteristics of MI (Malouin, et al. 2004; Sabaté, et al. 2004).

5.5 Study limitations

Although the present study revealed interesting results for the development of fNIRS controlled feedback systems by classifying brain activation during MI performance, it was nevertheless subject to a number of limitations.

First, a potential limitation may be related to the cortical locations recorded in this study. The lack of simultaneous recording of the ipsilateral hemisphere might have limited our results. As observed in previous studies, brain activation in response to motor and imagined actions can differ depending on the recorded hemisphere (Ang, et al. 2008; Babiloni, et al. 2004; Liang, et al. 2008).

Second, aspects related to the experimental block design used in our study might require consideration. One aspect is the possibility of ordering effects that in general can arise from the serial order in which tasks are performed and potentially lead to either deterioration or improvement in performance of successive tasks. In our design, although the order of the MI tasks was randomized, all subjects first executed the hand motor task prior to imagery that could have led to either inhibition or facilitation of MI performance.

Further, the experimental design was based on periodic alternations of 20 sec stimulation periods and 20 sec rest periods. This may be problematic, as the regular intervals may induce systemic physiological noise contributions from the respiratory, cardiac, and blood pressure

signals, such as Mayer waves. Future studies need to take account of this aspect by applying irregular intervals, e.g. 20 sec stimulation periods and 30 sec rest periods.

Third, aspects related to subject selection need to be mentioned. We did not include subjects with low imagery ability as documented by the KVIQ-10, which may weaken our previous statements about assessing MI using questionnaires. And, as mentioned above, subjects did not receive individualized training in MI performance as it has been done in a previous fNIRS controlled BCI (Sitaram, et al. 2007). The inter-subject variability in the hemodynamic response patterns observed in our study might have been therefore higher in our untrained subjects as it would have been occurred after pre-experimental training.

Last, we did not monitor electromyography (EMG) to exclude muscular activation during imagery. Although, task-unrelated hand movements during MI performance were documented by the experimenter, it could be claimed that weak EMG activity might have been present during the imagery tasks. However, previous neuroimaging studies suggested that brain signals during imagery of hand motor tasks are not correlated with EMG activation (Porro, et al. 1996). Therefore, the probability is small that differences in muscular activity have influenced our results.

6 Conclusion

The present study expanded previous fNIRS studies by investigating MI performance in response to positive and negative feedback. The results show evidence of distinct oxygenation patterns in signal amplitude. Although, our results and the limitations of the current study require further evaluation, this study may contribute to the development of fNIRS controlled feedback systems.

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Figure 1: Experimental block design. Each condition consisted of 15 stimulation (20 seconds) alternated with rest periods (20 seconds). Each condition lasted 10 minutes; total measurement length was 40 minutes.

Figure 2: Arrangement of light sources (L1, L2, L3, and L4) and detectors (D1, D2, D3, and D4) on the sensor. The centre of the sensor was positioned over C3. Ten channels were considered for analysis (red).

Figure 3: Inter-subject differences of signal amplitude. (Left) Mean O_2Hb concentration changes of all subjects. Inter-subject differences are shown by the standard deviation (SD) (red lines). (Right) Mean HHb concentration changes of all subjects.