Detecting Mental Calculation Related Frontal Cortex Oxygenation Changes for Brain Computer Interface Using Multi-Channel Functional Near Infrared Topography

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Abstract. Multi-channel functional near infrared topography (fNIRT) is a non-harmful, non-invasive and safe optical imaging technique that allows the simultaneous acquisition of oxygenated and deoxygenated hemoglobin concentration changes on the scalp. This study was aimed at investigating the potential use of fNIRT in association with a cognitive system, namely the working memory, for brain-computer interface (BCI). By using a 8-channel fNIRT system (NIRO-200 with multi-fiber adapter, Hamamatsu Photonics), we demonstrated in eight subjects that the mental calculation provokes over the frontal cortical region a significant increase in oxygenated hemoglobin and a concomitant smaller and delayed significant decrease in deoxygenated hemoglobin in all measurements points of both hemispheres. This result indicates that cortical regions involved in higher cognitive functions may serve as a readily self-controllable input for BCI fNIRT based applications.

Keywords: Brain-Computer Interface; Near Infrared Spectroscopy; Funtional Imaging; Frontal Lobe; Mathematical Calculation

1. Introduction

One of the critical issues in brain–computer interface (BCI) research is how to translate a person's intention into brain signals for controlling computer programs. Several non-invasive BCI modalities have been explored such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), magnetoencephalography or electroencephalography (EEG) techniques, which all have advantages and shortcomings. Although EEG outperforms remaining techniques as an excellent candidate for BCI, in the last 5 years several groups investigated the possibilities, in this application, of functional near-infrared topography (fNIRT). fNIRT is a non-harmful, non-invasive and safe optical imaging technique that allows the simultaneous acquisition of oxygenated and deoxygenated hemoglobin concentration changes ([O_2Hb] and [HHb], respectively) from an array of optical fibers on the scalp [Wolf et al., 2007]. Based on the tight coupling between neuronal activity and oxygen delivery, [O_2Hb] and [HHb] are considered as indicators of cortical activation [Hoshi, 2007]. fNIRT provides a reliable measure of brain function, as indicated by the correspondence between fNIRT, fMRI and PET measures. A crucial question not yet addressed in depth is what mental tasks are suitable for BCIs based on fNIRT. The motor system was the primary focus of fNIRT studies, where signals were obtained during real or imagined motor responses (Table 1). However, the oxygenation changes revealed so far in the motor areas are extremely localized and relatively small with respect to the larger oxygenation changes found in the frontal areas upon different cognitive tasks. Indeed, cognitive brain systems are attractive BCI candidates, since they may be more agreeable to conscious control, producing a better regulation of magnitude and duration of localized brain activity.

This study was aimed at investigating the potential use of fNIRT in association with a cognitive system for BCI, namely the working memory system, which has been investigated extensively with fMRI and PET. The working memory system was tested by a mental calculation task of moderate difficulty.

Table 1. *BCI developments using functional NIRT.*

Task	*Cortical area*	*Number of subjects*	*NIRT instrument*	*Number of channels*	*Author [reference]*
M	Parietal	1	Imagent, ISS, USA	48	Kohlenberg 2006
C	Frontal	9	Imagent, ISS, USA	48	Luu 2009
C	Frontal	8	CW prototype, USA	16	Ayaz 2007
M	Parietal	4	OMM-3000, Shimadzu, Japan	64	Tsubone 2007a
M	Parietal	8	OMM-3000, Shimadzu, Japan	64	Tsubone 2007b
MI	Parietal	3	CW prototype, Ireland	1	Coyle 2004
MI	Parietal	3	CW prototype, Ireland	1	Coyle 2007
C	Frontal	2	CW prototype, Ireland	12	Soraghan 2008
M	Parietal	1	OMM-3000, Shimadzu, Japan	6	Muroga 2006
MI	Parietal	5	OMM-1000, Shimadzu, Japan	20	Zhang 2006
M	Frontal	10	OMM-3000, Shimadzu, Japan	10	Ogata 2007
M, MI	Parietal	5	OMM-1000, Shimadzu, Japan	20	Sitaram 2007
MI	Parietal	2	OMM-3000, Shimadzu, Japan	17	Khoa 2008
C	Parietal	1	OTIS, Archinoetics, USA	1	Wubbels 2007
C	Frontal	15	CW prototype, Austria	1	Bauernfeind 2008
C	Frontal	4	ETG-4000, Hitachi, Japan	24	
C	Frontal	40*	CW prototype, Japan	1	Naito 2007

BCI: brain-computer interface; C: cognitive; CW: continuous wave; M: motor; MI: motor imagery; NIRT: near infrared topography; *: amyotrophic lateral sclerosis patients.

2. Material and Methods

After receiving a complete explanation of the purpose and the procedures of the study, eight healthy adults (four male; mean age: 27±2 years) gave their written consent. Heart rate was monitored by a pulse oximeter equipped with a finger probe (Nellcor N600, USA).

A 8-channel fNIRT system (NIRO-200 with multi-fiber adapter, Hamamatsu Photonics K.K., Japan) was used to measure frontal changes in [O_2Hb] and [HHb]. Two optical fiber bundles (2.5 m length; 3 mm diameter) carried the light to the left and the right frontal cortex; whereas eight optical fiber bundles of the same size (4 for each lobe) collected the light emerging from the frontal areas. The two illuminating bundles and the collecting ones were assembled into a specifically designed flexible probe holder ensuring that the position of the 10 optodes, relative to each other, was fixed. The 8 fNIRT measurement points (channels) were defined as the midpoint of the corresponding detector-illuminator pairs (distance set to 3 cm) (see Fig. 1). The channels 8, 5, 4, and 1 corresponded to Fp1, AF3, Fp2, and AF4 respectively, according to the extended international 10/20 system of electrode placement. The quantification of concentration changes, expressed in ΔμM, was obtained by including an age-dependent constant differential pathlength factor ($5.13+0.07\times age^{0.81}$). Data were acquired at 1 Hz and transferred online from the NIRO-200 monitor to a computer.

Subjects, seated in a comfortable armchair, were requested to perform mentally a 60-s arithmetic task. After a visual cue, subjects subtracted serially a 2-digit number from a 4-digit number (e.g., 1652-14) as quickly as possible (self-paced).

Statistical analyses were performed using the SigmaStat 3.5 package. The average values were expressed as mean±SD. The criterion for significance was $p<0.05$. In order to determine the significance of [O_2Hb] and [HHb] changes, one-way repeated measures analysis of variance (one-way RMANOVA) and post-hoc Tukey test were performed. The control condition was the mean value of the 30-s rest condition. To examine the effect of the cognitive task on [O_2Hb] and [HHb] changes, areas under the curve (AUCs) were computed using the curves over the time associated with the mental calculation. This analytic approach is well established in the quantification of concentration change over time and it would be maximally sensitive to task-related changes on [O_2Hb] and [HHb] regardless of the shape of the response profile. The AUC of the rest period was subtracted to the AUC calculated over the task period. Resulting data were analyzed by using a two-way analysis of variance model using post-hoc Tukey test to determine the significance of individual changes between two experimental factors [hemisphere (2)×channel (4)].

3. Results

Figure 1 shows the grand average of the [O_2Hb] and [HHb] changes in the eight frontal cortex measurement points during the mathematical calculation. During the task period, a significant increase in [O_2Hb] accompanied by a smaller and delayed significant decrease in [HHb] was observed in all measurements points of both hemispheres.

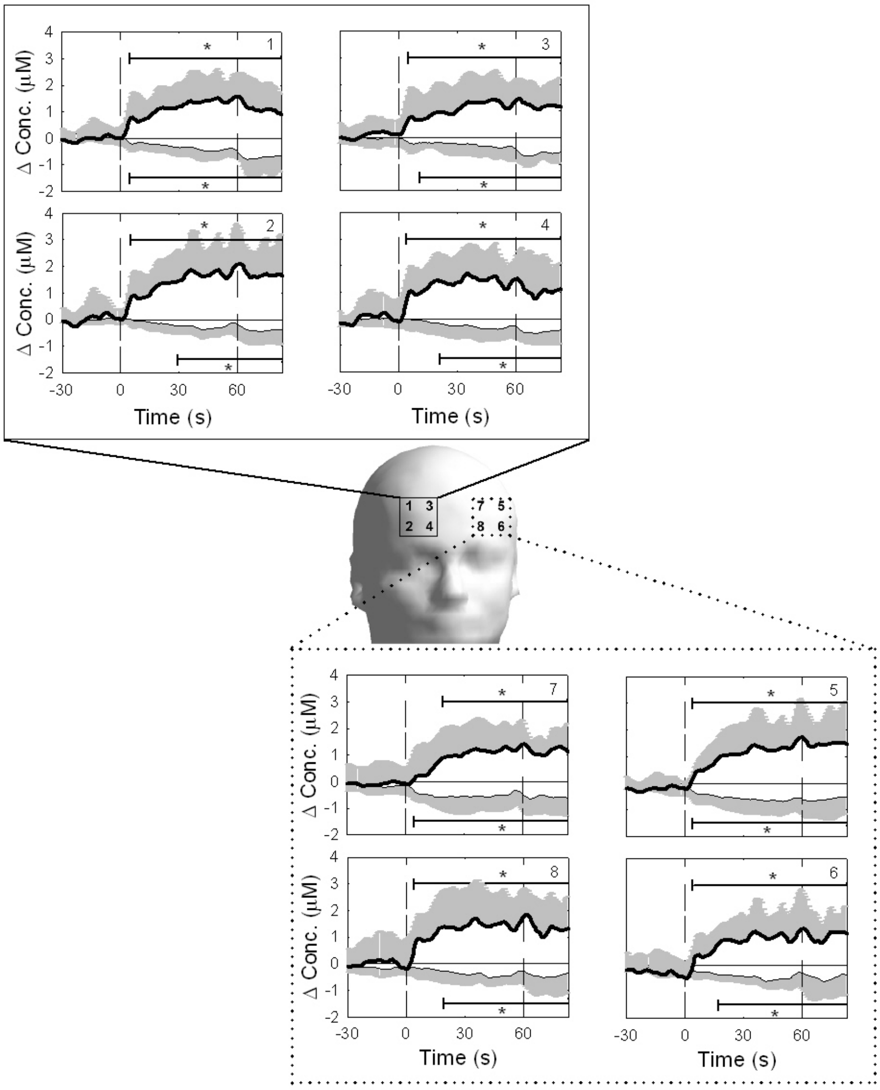

Figure 1. *Cortical oxygenation changes in response to the mathematical task in 4 measurement points of the right and left frontal regions (upper and lower boxes, respectively). Frontal cortex was found activated (increase in [O_2Hb] and a concomitant decrease in [HHb]) throughout the investigated frontal region. The vertical dashed lines indicate the period of the mathematical calculation; the horizontal lines indicate the significance interval. (N= 8; means±SD; $p<0.05$).*

After the end of the task [O_2Hb] and [HHb] showed a tendency to return gradually to their corresponding pre-task values. It is not clear the reason why O_2Hb and HHb recovered very slowly. One possible explanation could be that these subjects were still using the prefrontal cortex for thinking further about the calculation, and for keeping in their mind the result of the calculation.

Interestingly, [O_2Hb] increased significantly 6±5 s after the onset of the task, conversely [HHb] decreased significantly 14±9 s afterward. Based on the tight coupling between neuronal activity and oxygen delivery, this oxygenation pattern can be interpreted as an indicator for cortical activation. Two-way analysis of variance carried out on [O_2Hb] and on [HHb] changes did not show any significant main effect for hemisphere and for channel. In addition, any significant hemisphere x channel interaction was found.

4. Discussion

We reported on a proof of principle study for the potential use of fNIRT in association with a cognitive system for BCI, namely the working memory system. These preliminary results demonstrate that mental calculation reliably activates after few seconds the working memory network measured as [O_2Hb] increase.

Due to the small sample size, the short term nature of the study and the fact that all subjects were able-bodied, these results cannot be easily generalized. However, these data and those by others (Table 1) suggest that cognitive tasks as well as motor and movement imagery tasks are suitable for BCI based on fNIRT. In conclusion, these results indicate that cortical regions involved in higher cognitive functions may serve as a readily self-controllable input for BCI-fNIRT based applications.

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