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Focal frontal (de)oxyhemoglobin responses during simple arithmetic

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ABSTRACT

Near-infrared spectroscopy (NIRS) is a functional brain imaging method able to study hemodynamic changes during cortical activation. We studied the changes of oxy- and deoxyhemoglobin ([oxy-Hb], [deoxy-Hb]) with a 52-channel NIRS system during simple mental arithmetic in ten healthy volunteers over the prefrontal cortex. We found that eight of the ten subjects showed a relative focal bilateral increase of [oxy-Hb] in the dorsolateral prefrontal cortex (DLPFC) in parallel with a decrease in the medial area of the anterior prefrontal cortex (APFC). The [oxy-Hb] response in left DLPFC and APFC was significant, while the [deoxy-Hb] response was clearly smaller and not significant. These observations were discussed within the context of "focal activation/surround deactivation".

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1. Introduction

Near-infrared spectroscopy (NIRS) is a recently developed technique that can reveal hemodynamic and metabolic changes during cortical activation. NIRS has been used to study hemodynamic responses (changes of oxy- and deoxyhemoglobin ([oxy-Hb], [deoxy-Hb])) to cognitive, visual, visuomotor and motor tasks (Franceschini et al., 2003; Herrmann et al., 2005; Herrmann et al., 2008; Hofmann et al., 2008; Shimada et al., 2004; Tanida et al., 2004; Wriessnegger et al., 2008). It is widely accepted that increases in [oxy-Hb] and slight decreases in [deoxy-Hb] are typical for activation (Buxton et al., 2004; Obrig et al., 1996; Strangman et al., 2002). Especially the PET study of Fox and Raichle (1986) could show that such a pattern of increasing [oxy-Hb] and decreasing [deoxy-Hb] is considered to reflect brain activation.

It is known that the frontal cortex plays a major role in solving a mental arithmetic (MA) task. Previous neuroimaging studies using functional magnetic resonance imaging (fMRI) exploring arithmetic tasks revealed left-sided and/or bilateral activation of the ventrolateral (VLPFC) and dorsolateral (DLPFC) prefrontal cortex (Kawashima et al., 2004; Menon et al., 2000; Rickard et al., 2000) during simple arithmetic operations like one-digit addition, subtraction and multiplication tasks.

Indeed, several NIRS studies have demonstrated the implication of the prefrontal cortex (PFC) during MA (Tanida et al., 2004; Bauernfeind et al., 2008; Hock et al., 1995; Hoshi et al., 1994; Hoshi and Tamura, 1993) but most of them used either only one or two NIRS channels. For example Tanida et al. (2004) investigated the relationship between asymmetry of the prefrontal cortex activity and the automatic nervous system (ANS) response during a mental arithmetic (MA) task. They found increases of [oxy-Hb] and total hemoglobin (=[oxy-Hb] + [deoxy-Hb]) associated with decreases of [deoxy-Hb] in the bilateral PFC. In contrast, Bauernfeind et al. (2008) performed a one-channel NIRS-study on MA tasks resulting in a prefrontal decrease of [oxy-Hb]. These different results might be due to the different type and duration of the MA tasks, the positioning of the optodes and the limited number of channels.

In recent years, NIRS technology was used alternatively to the electroencephalography (EEG) as a sensor technology for a non-invasive Brain-Computer Interface (BCI; Coyle et al., 2007; Sitaram et al., 2007; Luu and Chau, 2009; Bauernfeind et al., 2008; Pfurtscheller et al., in press). In the case of a NIRS-based (optical) BCI the user performs a mental task (e.g. motor imagery, mental calculation, and auditory imagery) and induces herewith hemodynamic changes recordable over the prefrontal or motor cortex areas. The optode placement especially over the prefrontal cortex is useful, because such a NIRS system is more practical and user-friendly and so suitable for application out of the lab. Furthermore online signal detection with an optical BCI could be relatively easier with antagonistic activation patterns, which means Hb responses displaying an opposite polarity (e.g. [oxy-Hb] increase and decrease) at different optode locations. Taken these into account the aim of the present study was to determine whether a simple arithmetic task can elicit focal changes of [oxy-Hb] and [deoxy-Hb] over prefrontal optode locations which can be used for future optical BCI systems.

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2. Material and methods

2.1. Subjects and experimental procedure

The investigations were carried out on a group of ten paid University students (five males and five females, all right-handed) aged 26.1 ± 2.7 years (mean ± SD). The subjects abstained from caffeine before recording, were seated in a comfortable armchair, and gave written informed consent before the experiment. The study was approved by the ethics committee of the Medical University of Graz.

The subjects were asked to serially subtract a one-digit number from a two-digit number (e.g. 97 − 4) as quickly as possible for 12 s. The numbers were presented visually on the monitor at the beginning of each trial. There was a 28 s pause at the end of each trial, so each trial lasted 40 s. During the pause, the subjects were instructed not to move and to stay relaxed by just looking at the black screen. In sum 24 trials were collected. To avoid enhancement of 3rd order blood pressure waves (De Boer et al., 1986) or their sub-harmonics an experimental paradigm with 12 s activity phase and 28 s pause was chosen. It is very important to control this type of waves since they have large magnitudes and can mask task-related changes (Bauernfeind et al., 2008; Coyle et al., 2004; Elwell et al., 1999).

2.2. Data acquisition and processing

A continuous wave system (ETG-4000, Hitachi Medical Co., Japan) was used to record brain oxygenation. The multi-channel system measures the change of [oxy-Hb] and [deoxy-Hb] in the unit of mM mm and consists of 16 photo-detectors and 17 light emitters (3 × 11 grid), resulting in a total of 52 channels. The sampling rate was set to 10 Hz. The distance between source and detector was 3 cm. The lowest line of channels was arranged along the FP1–FP2 line of the international EEG 10–20 system, with channel 48 exactly at the FP1 position (Fig. 1). In order to allow a probabilistic reference to cortical areas underlying the measurement channels and to make the results comparable to results provided by similar fMRI studies (e.g. Kawashima et al., 2004; Menon et al., 2000; Rickard et al., 2000) we used a procedure which projects topographical data based on skull landmarks into a 3D reference frame (MNI-space, Montreal Neurological Institute) optimized for NIRS analysis (Singh et al., 2005). So for each NIRS channel position (Fig. 1), a set of MNI coordinates (x, y, and z) with an error estimated (SD) was calculated. For further details on the corresponding anatomical structures see Okamoto et al. (2004).

After a visual inspection of the raw NIRS data, channels with poor signal quality were marked (in three subjects; two, four and nine channels respectively). Afterwards, a common average reference (CAR) spatial filter was used to remove global influences (e.g. changes in heart rate or respiratory influences). Therefore, for every time point, the mean of all non-marked channels was calculated and subtracted from each channel. For artifact reduction, a 0.09 Hz low pass Butterworth filter of order 4 with 60 dB in the stop band was designed. Additionally, a 0.01 Hz high pass filter was used to remove baseline drifts. For further details, see Bauernfeind et al. (2008). The subject with nine marked channels displayed too many artifacts and was removed from further analysis and a second subject showed no reliable pattern and was also omitted.

2.3. Calculation of task-related changes and topographic distribution

The mean task-related concentration changes of [oxy-Hb] and [deoxy-Hb] referred to a 10 s baseline interval prior to the task (seconds − 10 to 0) were calculated for each non-marked channel. For the marked channels, the changes were calculated by interpolating the surrounding channels.

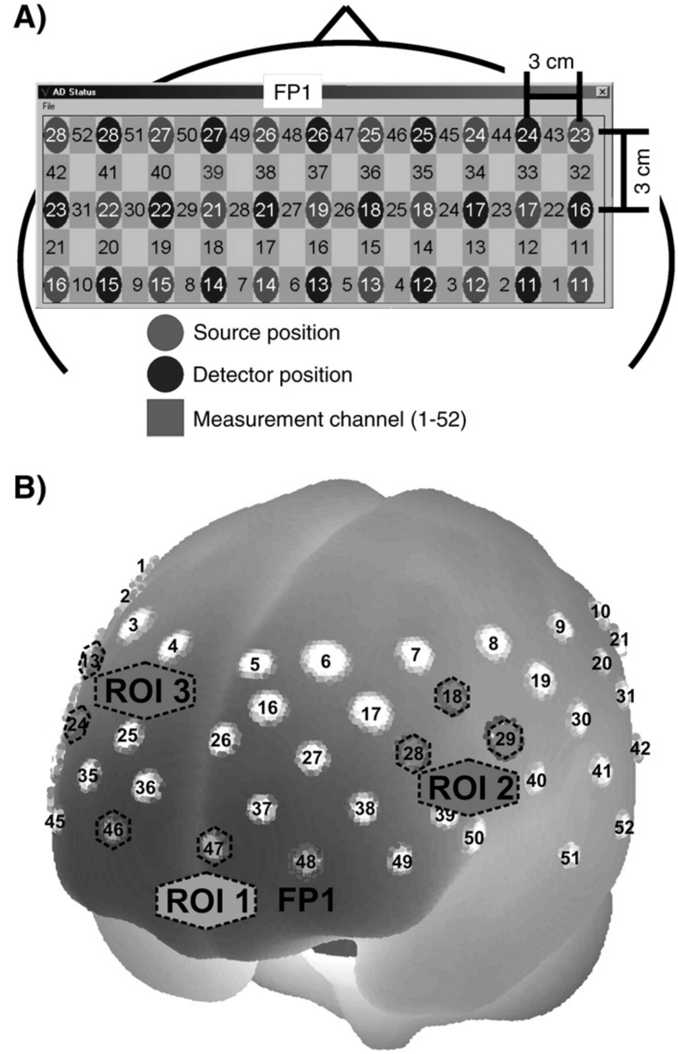

Fig. 1. A) Schematic illustration of the multi-channel array (52 channels, 3 × 11 grid). B) Projections of the NIRS channel positions on the cortical surface. Positions are overlaid on a MNI-152 compatible canonical brain which is optimized for NIRS analysis (Singh et al., 2005). The lowest line of channels was arranged along the FP1–FP2 line of the international EEG 10–20 system, with channel 48 exactly at the FP1 position. The centers of the circle regions represent the locations of the most likely MNI coordinates for the NIRS channel projected on the cortical surface. The edges represent the boundaries defined by the standard deviation.

The topographic distributions during the tasks are further visualized by plotting the [oxy-Hb] and [deoxy-Hb] values at their corresponding spatial position. A 2-D interpolation on a fine Cartesian grid was used to generate a scalp distribution. Two different points in time are illustrated. The first point between 0 and 2 s corresponds to the cue presentation and start of the task; the second point between 10 and 12 s corresponds to the end of the task. [oxy-Hb] and [deoxy-Hb] are visualized in different plots, but use the same scale. Increases are plotted in blue and decreases in red (no activation is plotted in white).

Examples of the hemodynamic responses at all 52 channels are displayed in Figs. 2 and 3.

2.4. Statistical analysis

Two 3 × 5 repeated measures of analyses (ANOVA) on the data were performed separately for [oxy-Hb] and [deoxy-Hb]. The two factors, “regions of interest” (ROI: frontal, left, right), and “time” (baseline, seconds 8–10, seconds 10–12, seconds 12–14, and seconds

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