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Development, set-up and first results for a one-channel near-infrared spectroscopy system

Entwicklung, Aufbau und vorläufige Ergebnisse eines Einkanal-Nahinfrarot-Spektroskopie-Systems

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Abstract

Near-infrared spectroscopy (NIRS) is a non-invasive optical technique that can be used to assess functional activity in the human brain. This work describes the set-up of a one-channel NIRS system designed for use as an optical brain-computer interface (BCI) and reports on first measurements of deoxyhemoglobin (Hb) and oxyhemoglobin (HbO_2) changes during mental arithmetic tasks. We found relatively stable and reproducible hemodynamic responses in a group of 13 healthy subjects. Unexpected observations of a decrease in HbO_2 and increase in Hb concentrations measured over the prefrontal cortex were in contrast to the typical hemodynamic responses (increase in HbO_2, decrease in Hb) during cortical activation previously reported.

Keywords: deoxyhemoglobin; mental arithmetic tasks; near-infrared spectroscopy (NIRS); oxyhemoglobin.

Zusammenfassung

Die Nahinfrarot-Spektroskopie (NIRS) ist eine nichtinvasive optische Technik, welche die Erfassung funktioneller Aktivitäten im menschlichen Gehirn ermöglicht. Diese Arbeit beschreibt den Aufbau eines Einkanal-NIRS-Systems, konzipiert für eine zukünftige Verwendung als optisches Brain-Computer-Interface. Weiters werden erste Ergebnisse der Konzentrationsänderungen von Oxyhämoglobin (HbO_2) und Deoxyhämoglobin (Hb) während mentaler arithmetischer Aufgaben, gemessen an einer Gruppe von 13 gesunden Probanden, vorgestellt. Die Messposition wurde dabei über dem präfrontalen Kortex gewählt. Bei diesen Messungen wurden relativ stabil reproduzierbare hämodynamische Konzentrationsänderungen gefunden. Unerwartet war dabei die Messung einer Erhöhung der Hb- und einer Erniedrigung der HbO_2-Konzentration bei Aktivierung, welche einem der Literatur gegenläufigen Verlauf entspricht.

Schlüsselwörter: Deoxyhämoglobin; mentale arithmetische Aufgaben; Nahinfrarot-Spektroskopie; Oxyhämoglobin.

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Introduction

General

Neural activity, detected by electroencephalography (EEG), within the cortex is a typical physiological signal often used for brain-computer interfaces (BCI) [1, 23, 29]. Non-invasive near-infrared techniques can also be used to detect functional activity of the cerebral cortex [4] and are an alternative to electrical signals for BCI communication [2, 25]. The aim of the present study was to develop a near-infrared spectroscopy (NIRS) system for use as an optical BCI. Such a system is more practical and user-friendly [4] and overcomes the limitations and restrictions of EEG acquisition, such as the influence of electrooculogram (EOG), electrode failure and conductivity problems.

Near-infrared spectroscopy

NIRS is a non-invasive optical technique for assessment of functional activity in the human brain. The technique uses an optical window in the NIR light spectrum identified by Jöbsis [16]. Within this spectral range (approx. 630–1300 nm), light can penetrate the cranium and reach sufficient depth [20] to allow investigation of the metabolism in the cerebral cortex [16]. NIR light, which invades tissue at a particular place at the head, interacts with the tissue in several ways. The beam becomes diffuse through photon scattering in the tissue. Scattered photons follow a random path through the tissue, resulting in partial absorption of these photons [e.g., through chromophores such as deoxyhemoglobin (Hb) and oxyhemoglobin (HbO_2)]. Another part is reflected back and leaves the head several centimetres away from the source location [20]. Theoretical and experimental investigations by Okada et al. [20] revealed that photons travel in a crescent-shaped path from the source to the detector. If back-reflected photons are detected over a longer time period, it is possible to draw conclusions about metabolic changes in the tissue area penetrated by the photons. These changes, such as increased or decreased blood flow and changes in tissue oxidation, are associated with brain activity and modify the tissue characteristics. This means that the absorption and scattering of

photons change and hence affect the detected light. Therefore, a qualitative measure of brain activity can be obtained.

Neurovascular coupling

Neurovascular coupling is a term for the interaction between neuronal (electrical) activity, cortical blood circulation and oxygen consumption in brain tissue. As described by Wolf et al. [28], three main factors affect Hb and HbO_2 concentrations in the brain and consequently the attenuation of NIR light: the cerebral metabolic rate of oxygenation ($CMRO_2$), cerebral blood flow (CBF) and cerebral blood volume (CBV). During neuronal activation, changes in the $CMRO_2$, CBV and CBF partially occur at the same time.

One aim of the present study was to introduce the components of a one-channel NIRS system and to report first results for Hb and HbO_2 changes during different mental arithmetic tasks (MAT), planned as control signals for a future BCI application. A further goal was to investigate the intra- and inter-subject variability of mental signals.

Materials and methods

NIRS measurement

Biological tissue is a highly scattering medium and the path length of photons thus increases as a result of scattering events. This elongated path length leads to higher scattering losses. To describe the light absorption process, the modified Beer-Lambert law [8]

$$A = \log\left(\frac{I_0}{I}\right) = \alpha\ c\ x\ d + K \tag{1}$$

needs to be used, where A is the attenuation, I_0 [mW] is the light intensity entering the tissue, I [mW] is the light intensity exciting the tissue, α [(mol/l)$^{-1}$ m^{-1}] is the specific extinction coefficient of the absorber (data taken from [3]), c [mol/l] is the concentration of the absorber, hereafter referred to as the molar concentration [M], x is the differential path length factor (estimated factor, based on empirical studies [10]), d [m] is the geometric distance between the emitter and the detector, and K is a term influenced by the measurement geometry accounting for scattering losses and can be considered as time-invariant in a small time interval. HbO_2 and Hb, which are the two chromophores of interest in this work, have different attenuation spectra. The concentrations of all other absorbers such as water and lipids and the absorption of the surface tissue are assumed to remain constant during measurement. Therefore, the signal intensity detected depends on the sum of the absorption of HbO_2 and Hb.

One approach that can be used for NIRS measurement is the continuous wave (CW) method, whereas two wavelengths are necessary to calculate the two concentrations of interest (HbO_2 and Hb). With this method, only relative absorption changes can be detected. Concentration changes in HbO_2 and Hb between two time points (t_1 and t_2, $t_1 < t_2$) are calculated according to the following equation:

$$\begin{aligned}\Delta C = \alpha^{-1}\Delta A &= \alpha^{-1}\begin{pmatrix}\Delta A_{670}\\ \Delta A_{890}\end{pmatrix}\\ &= \begin{pmatrix}\alpha_{670,\mathrm{Hb}} & \alpha_{670,\mathrm{HbO}}\\ \alpha_{890,\mathrm{Hb}} & \alpha_{890,\mathrm{HbO}}\end{pmatrix}^{-1}\begin{pmatrix}\dfrac{\log\dfrac{I_{670}(t_1)}{I_{670}(t_2)}}{x_{670}d}\\ \dfrac{\log\dfrac{I_{890}(t_1)}{I_{890}(t_2)}}{x_{890}d}\end{pmatrix}\\ &= \begin{pmatrix}\Delta C_{\mathrm{Hb}}\\ \Delta C_{\mathrm{HbO}}\end{pmatrix}.\end{aligned} \tag{2}$$

Hardware

Inspired by the work of Coyle [4], a one-channel NIRS system (Figure 1) was developed. With this system, characteristic hemodynamic responses during cognitive, visual or motor tasks can be measured in real time. The system uses the CW method and operates at two different wavelengths. Two light-emitting diodes (LEDs) at wavelengths of 670 and 890 nm (L6112-01 and L2656-03, Hamamatsu Photonics K.K., Hamamatsu, Japan) are used as light sources. The LEDs were placed in direct contact with the scalp. For light detection, a single avalanche photodiode (C5460-01, Hamamatsu Photonics K.K.) connected to the scalp via an optical fibre with a diameter of 2.5 mm was used. The distance d between the LED sources and the detector was 3 cm, which corresponds to a penetration depth of approximately 2.5 cm [20]. To separate light emitted from the two sources, the amplitude of each LED was modulated with a sine oscillation (3 and 7 kHz). A dual lock-in amplifier (model 7265, AMETEK Signal Recovery, Oak Ridge, USA) was used to obtain the intensities at the two modulated frequencies. These intensities correspond to the two LED wavelengths. The modulation frequencies have no influence on the absorption coefficients, since they are only determined by the wavelengths of the LED lights. The output of the lock-in amplifier was recorded at 250 Hz using a data acquisition card (NI PCI-6024E, National Instruments, Austin, USA).

Artifact reduction and preprocessing

Artifacts that influence the recorded signals (Figure 2) include the pulse, respiration effects, Mayer waves [11], which are spontaneous low-frequency oscillations of ~0.1 Hz (see Figure 3A), and hair movements. Movement of hair, which is also an absorber of light in the NIR range, may cause instability of the detected signal [4]. The frequency of pulse waves is in the range between 1 Hz (60 bpm) and 2 Hz (120 bpm); compared to this, the activation responses of Hb and HbO_2 are much slower. After calculating Hb and HbO_2, a digital 3-Hz low-pass Butterworth filter of order 5 with an attenuation of 30 dB in the stop band was used to allow down-sampling to 10 Hz. For artifact reduction a 0.09-Hz low-pass Butterworth filter of order 4 with 60 dB in the stop band was

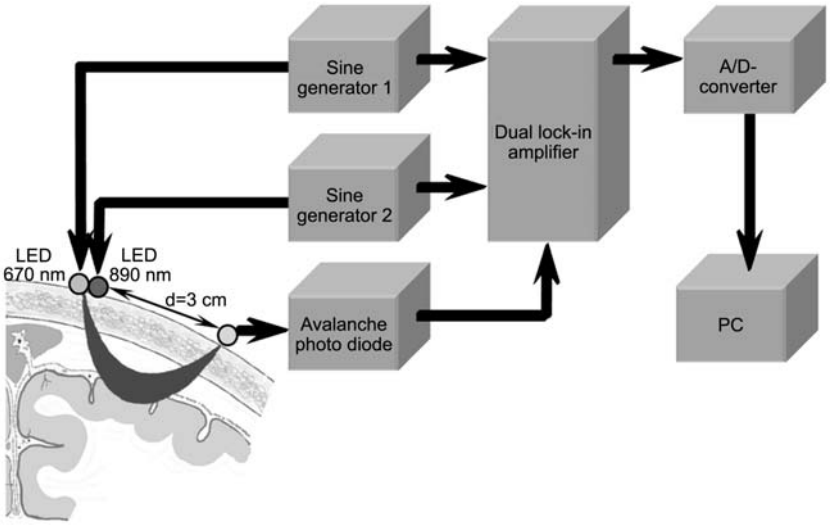

Figure 1 Components of the NIRS system developed at Graz University of Technology.
The system consists of two light-emitting diodes (670 and 890 nm) used as light sources, a single avalanche photodiode for light detection (source-detector spacing of $d = 3$ cm), a dual lock-in amplifier to separate the two intensities, and a data acquisition card to record the output of the lock-in amplifier at a sample frequency of 250 Hz.

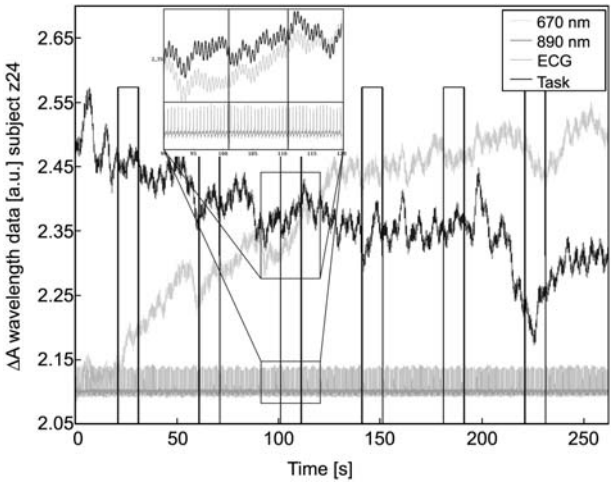

Figure 2 Output signals of the lock-in amplifier (ΔA wavelength data, 670 and 890 nm) for subject z24 (first recording) before any data processing.
The pulse (enlarged section) and effects of respiration influence both recorded signals. To relate oscillations in the signals to the heartbeat, the electrocardiogram (ECG) recorded from electrodes placed on the thorax is shown.

designed to remove pulse, hair movement and respiration effects. The effects of Mayer waves were not removed totally with this filter. In addition, a 0.01-Hz high-pass filter was used to remove baseline drift. The entire procedure for artifact reduction and preprocessing is shown in Figure 3B.

Experiments

Different MAT experiments were carried out as part of the present study. All experiments were in compliance with the World Medical Association Declaration of Helsinki. The aim of these experiments was to measure hemodynamic changes in Hb and HbO_2 caused by different MATs to identify stable and reproducible activation patterns. Hb and HbO_2 concentration changes were calculated from the output signals of the lock-in amplifier (Figure 2) using Eq. (2), processed and averaged over the number of tasks carried out.

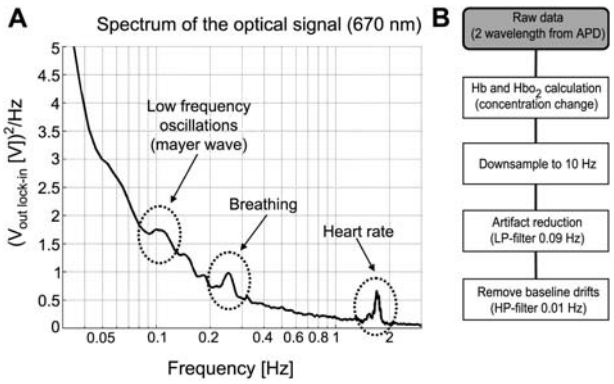

Figure 3 (A) Spectrum of the optical signal (670 nm, subject z24 first recording) with the influence of heart rate at frequencies of 1.6–1.8 Hz (equivalent to 96–108 bpm), respiration at 0.25 Hz (15 breaths/min) and Mayer waves at a frequency of 0.1 Hz. (B) Artifact removal and preprocessing procedure to remove pulse waves, hair movements, baseline drift and Mayer waves.

Experiment 1 Measurements were made for a group of five subjects (j8, l8, v4, y3 and z24; 3 males and 2 females, all right-handed) aged 28.4 ± 6.3 years (mean $\pm$ SD) using the custom-made one-channel system. The subjects were seated in a comfortable armchair. The sources and detector were placed on the frontal cortex, which is involved in arithmetic operations [12, 17, 26], 1.5 cm to the left and right of position FP1 (Figure 4A) according to the international 10/20 system for EEG recording. During the task, subjects had to perform an arithmetic operation. After a visual cue, the subjects had to subtract two three-figure numbers presented on a monitor within 10 s (e.g., 793-247), after which there was a pause of 30 s. One recording consisted of six trials and

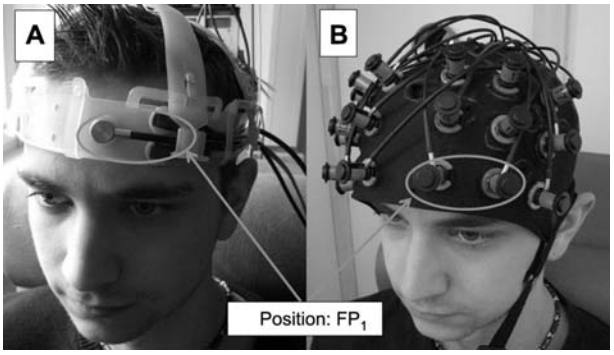

Figure 4 (A) Optode placement of the one-channel custom-made system (two light-emitting diodes, one detector) and (B) the multi-channel NIRS system. The multi-channel array was arranged so that channel 2 was placed over the FP1 position, similar to the one-channel system.

lasted approximately 4.3 min. The timing of the experiment is shown in Figure 5. Each subject performed four recordings on two days, resulting in 24 trials, except for subject j8, who performed 42 trials (seven recordings in 3 days).

Experiment 2 Measurements were made for a group of 10 subjects (ac9, ak2, ak3, ak4, ak7, al9, am1, j8, x20 and z24; 5 males and 5 females, all right-handed) aged 26.6±3 years using the one-channel system. The experimental set-up was the same as for experiment 1, but the task differed. Instead of performing a single subtraction, subjects had to perform repetitive subtractions within a time slot of 10 s (e.g., 97-4=93, 93-4=89, 89-4=85,…). For each subject, seven recordings were made on one day, resulting in 42 trials each.

Experiment 3 To validate the results obtained, additional measurements for four subjects (ak4, am1, j8 and z24) from the experiment 2 group were performed using a commercial multi-channel NIRS system (ETG-4000, Hitachi Medical Corporation, Osaka, Japan) and the same paradigm as task in experiment 2. The 24-channel array (a detailed drawing is given in Figure 8B) of this system was arranged so that channel 2 was placed over the FP1 position, similar to the one channel-system (see Figures 4 and 8A). The distance between the source and the detector is the same as in the one-channel system ($d=3$ cm). The system measures changes in Hb and HbO_2 concentrations in units of mmol mm.

Results

Experiment 1

Mean concentration changes in HbO_2 and Hb based on 24 trials for the five subjects, with the exception of subject j8 (42 trials), are displayed in Figure 6. The MAT was always performed between $t=0$ and 10 s (marked as the shaded area in Figure 6). All subjects showed a similar activation pattern involving a decrease in HbO_2 and an increase in Hb concentrations. Figure 2 also displays ΔA wavelength data (output signals of the lock-in amplifier, equivalent to the intensities detected) of the first recording for subject z24 before any data processing.

Experiment 2

The results for seven subjects based on 42 trials each are reported in Figure 7. Owing to exceptionally high intra-record variability caused by fitful breathing during the experimental epoch (e.g., a cessation of breathing when solving the MAT), three subjects did not deliver usable results and were excluded. This needs further investigation because the artifact reduction procedure shown in Figure 3B did not remove respiration effects in particular. Mean concentration changes in HbO_2 and Hb for the remaining seven subjects are displayed in Figure 7. The plots display the same significant decrease in HbO_2 and increase in Hb concentration in each subject (as in Figure 6), except for ak4, who exhibited decrease in Hb.

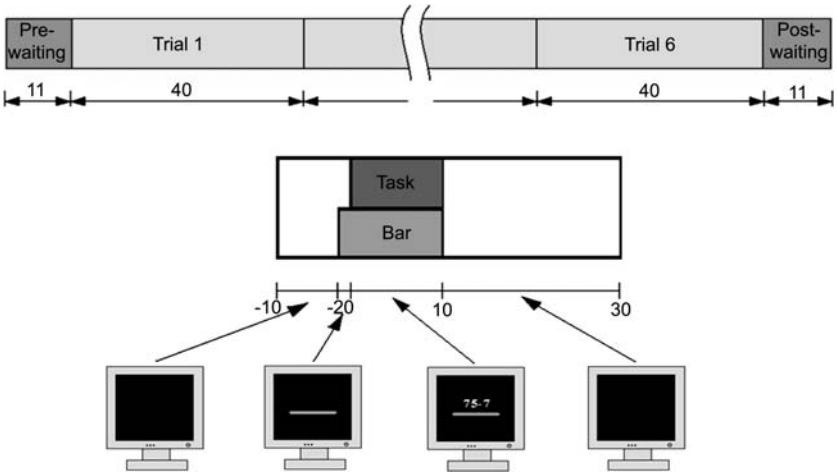

Figure 5 Time course of the MAT.
After a waiting period of approximately 11 s, six trials were performed. The time course of one of these trials is shown separately. At 2 s before the task started, a green bar appeared. After the cue (e.g., 793-274 for experiment 1 or 78-7 for experiments 2 and 3) the subject had to perform subtractions (repetitive for experiments 2 and 3) for 10 s until the green bar disappeared, which was followed by a pause of 30 s.

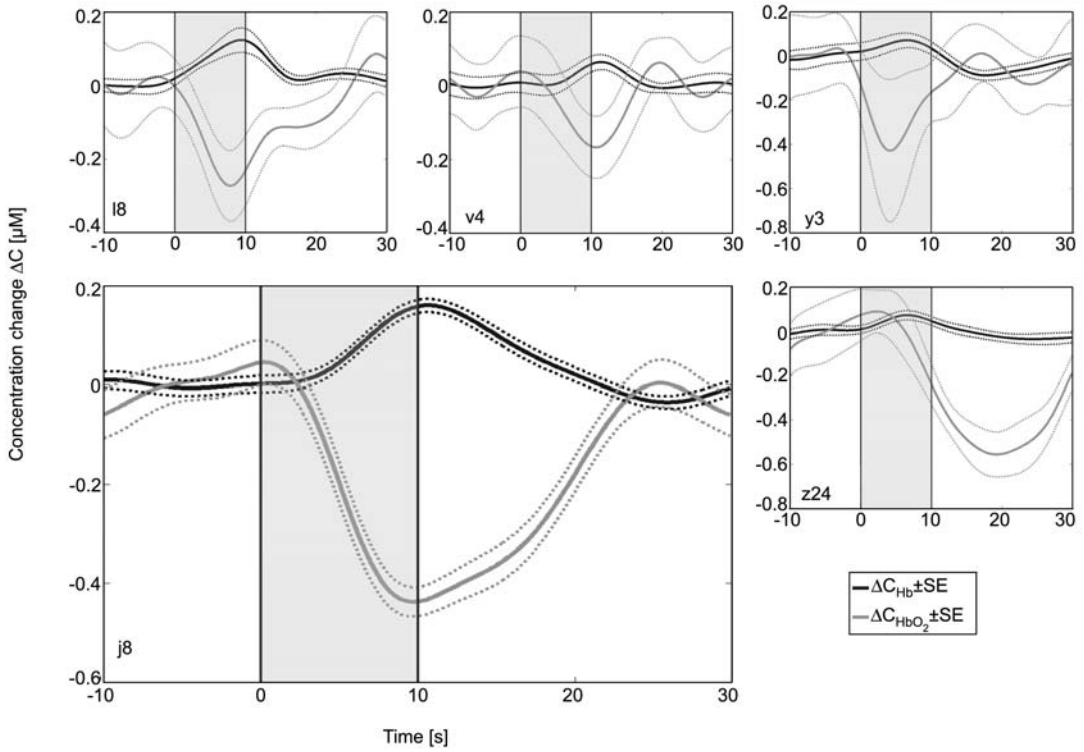

Figure 6 Concentration changes (mean ± SE) for subjects j8 (enlarged image), l8, v4, y3 and z24 during mental arithmetic experiment 1. The shaded area indicates the time period of the MAT. HbO_2 is plotted in light gray and Hb in black.

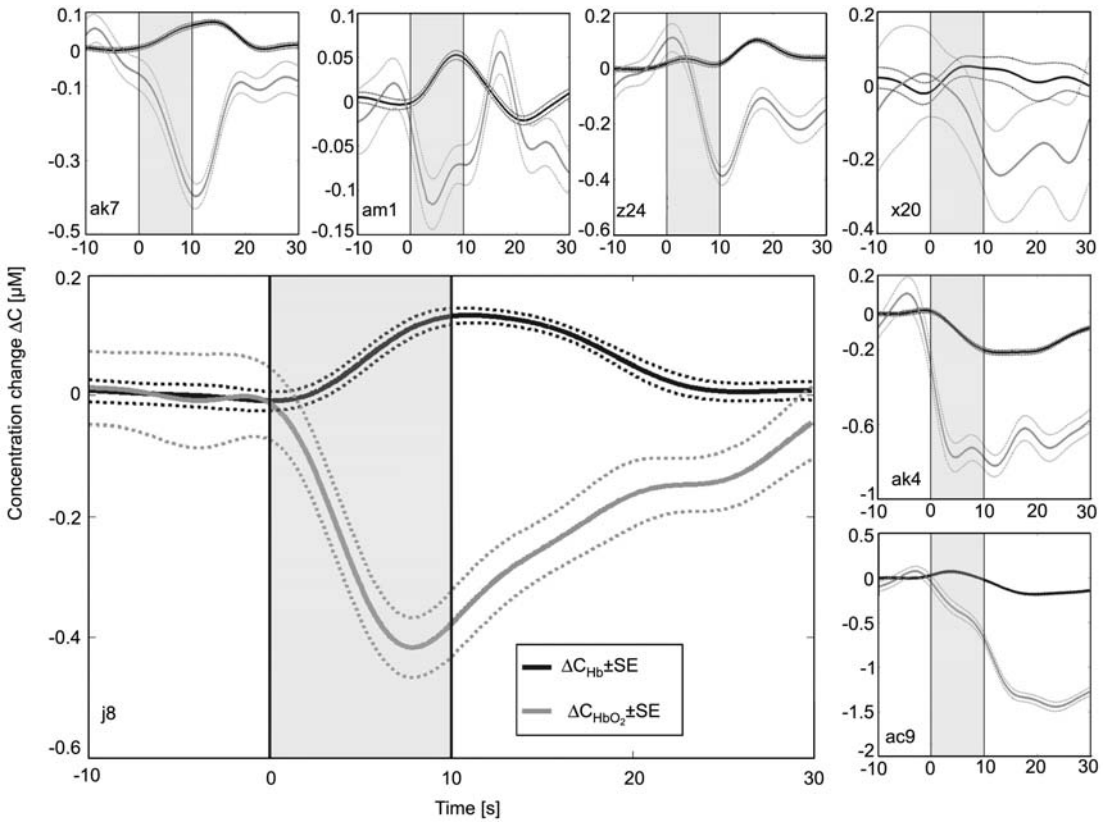

Figure 7 Concentration changes (mean ± SE) for 7 subjects (enlarged image, subject j8) during mental arithmetic experiment 2 (based on 42 trials for each subject).

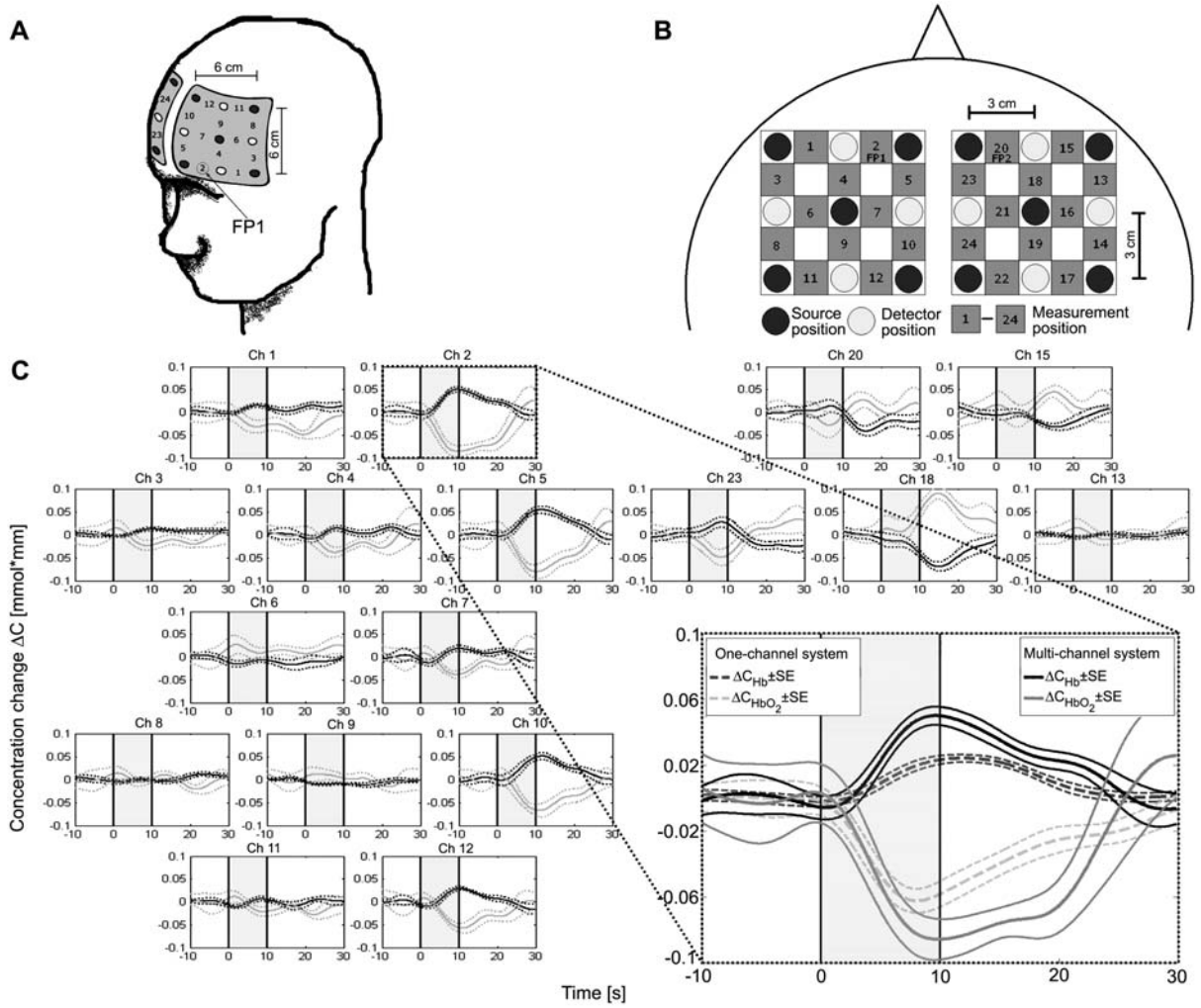

Figure 8 (A) Schematic illustration of the bilateral positioning of the two 3×3 arrays. (B) Positional layout (2×3×3) of the sources and detectors. (C) Mean concentration changes (mean±SE) of 24 channels for subject j8 (42 trials) during the MAT in experiment 3. The enlarged image shows channel 2, which was placed over the FP1 position, similar to the one-channel system. For comparison, the curve shape from experiment 2 is included in the enlarged image.

Experiment 3

Measurements were made for four of the subjects who took part in experiment 2 (ak4, j8, am1 and z24) and the result for one of these subjects (j8) is shown in Figure 8C. The large image shows channel 2, which was placed over position FP1, similar to the experiments with the one-channel system. To compare signals measured with the one-channel system and the multi-channel system, the result from experiment 2 (recalculated in mmol mm) is included in the large image. Cross-correlation of HbO_2 and Hb data (subject j8) for both systems was performed and revealed a highly significant ($p < 0.01$ for Hb and HbO_2) correlation. It could be demonstrated that independently of the NIRS system used, the same time course of Hb and HbO_2 concentration changes could be obtained.

Discussion and conclusion

The experiments with slightly different MAT (one subtraction for experiment 1 and repetitive subtractions within the task for experiments 2 and 3) revealed relatively reproducible results independent of the system used (custom-made one-channel system and commercial multi-channel NIRS system). Of special interest are the unexpected HbO_2 and Hb responses during the MAT. In all experiments with both NIRS systems, HbO_2 decreased and Hb increased. This is in contrast to the HbO_2 increase and Hb decrease reported in many studies, e.g., during hand movement and imagination tasks [4–6, 25] or during mental [15, 27] and verbal [14, 24] tasks. On the other hand, Hoshi and colleagues [15] found in 9 of 33 healthy subjects the same decrease in HbO_2 and increase in Hb concentrations over frontal regions of the dominant hemisphere during MAT as reported in this paper. However, the remaining 24 subjects showed the typical hemodynamic response. These observations were further confirmed by simultaneous positron emission tomography measurements. Quaresima [24], in addition to the typical activation response in 4 of 8 subjects, observed different patterns (lack of Hb decrease or an Hb increase) of cortical activation. In principle, one reason for such unexpected HbO_2 and Hb responses could be that extracortical (scalp) effects dominate the results, but for a source-detector spacing greater than

20 mm the intensely sensitive region is confined to the gray matter [13, 18] and a considerable amount of the signal changes originates from hemodynamic changes at the surface of the brain and in the gray matter [19]. Another argument supporting the assumption that the present data are cerebral signals is that the tissue permeated by the NIR light showed a clear vascular and metabolic response to the experimental task. This conclusion is confirmed by the results of experiment 3, which demonstrated that independent of the NIRS system used, the same task-dependent time course for Hb and HbO_2 concentration changes could be obtained (Figure 8C). Another reason for the unexpected responses concerns the task chosen, since neuronal activation might be more complicated during MAT compared to, for example, a simple hand movement task. In the case of hand movement, activated neurons are located in the motor area in the crown of the precentral gyrus and are fully penetrated by photons. Whereas hand movement involves a relative circumscribed area of some cm^2 in the motor and premotor cortex [21], the situation is more complex for a MAT. The neural networks involved in mental arithmetic operations are distributed over the frontal cortex, the inferior parietal lobule and other areas [7, 17] and are not located exactly under the optodes placed over the frontal brain. This was confirmed by the result of experiment 3 (Figure 8C). The signals in channels 5, 10 and 12 were similar to that in channel 2 (FP1 position); in contrast, the channels around channel 6 exhibited different signals. Thus, the frontal HbO_2 decrease and Hb increase may be explained as a surround effect of an HbO_2 increase and Hb decrease in areas not accessible by NIRS. Such a surround effect was reported during EEG recordings and is known as focal event-related desynchronization/surround event-related synchronization [22], but has also been observed in blood flow studies [9]. The reported decrease in regional cerebral blood flow arises in the somatosensory cortical area representing the body part when attention is directed to a distant body part [9].

The relatively low intra-subject variability in the time course of the Hb response during MAT and the reproducibility of the response within different MAT experiments provide evidence that a MAT is suitable for designing an NIRS-based mind switch [6]. A single-channel placement over the frontal cortex is more practical and user-friendly and thus is suitable for home applications. In addition, frontal placement avoids motion artifacts affected by hair movement. However, a strong limitation for NIRS-based mind switches is the nature of the hemodynamic response, which is of the order of several seconds. On the other hand, NIRS avoids some of the restrictions involved in EEG acquisition, such as the EOG influence, no conductive gel is required and the NIR light is non-ionizing and thus is suitable for long-term use.

Respiration effects were observed for the results for three subjects because these subjects aligned their respiration with the given task and in particular they stopped breathing during the calculation. This caused additional changes in Hb and HbO_2 that were superimposed on the changes caused by activation. Therefore, results for these subjects were omitted for the analysis.

The next steps towards a real-time system will involve enhancement of the signal-to-noise ratio for the hemoglobin response by reducing influences due to respiratory and blood pressure control systems (e.g., third-order blood pressure waves) and to apply advanced methods for single-trial detection. An important topic is also the search for optimal optode positions using a commercial multi-channel system.

In summary, NIRS is a cost-effective and non-invasive technology for physiological monitoring and may be suitable for future BCI applications. The results presented here demonstrate that the one-channel NIRS system developed is suitable for recording metabolic responses during MAT using frontally placed optodes. Our next step is to investigate the suitability of on-line response detection after applying different methods of signal-to-noise enhancement.

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