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Brain–computer interface using a simplified functional near-infrared spectroscopy system

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Abstract

A brain–computer interface (BCI) is a device that allows a user to communicate with external devices through thought processes alone. A novel signal acquisition tool for BCIs is near-infrared spectroscopy (NIRS), an optical technique to measure localized cortical brain activity. The benefits of using this non-invasive modality are safety, portability and accessibility. A number of commercial multi-channel NIRS system are available; however we have developed a straightforward custom-built system to investigate the functionality of a fNIRS-BCI system. This work describes the construction of the device, the principles of operation and the implementation of a fNIRS-BCI application, 'Mindswitch' that harnesses motor imagery for control. Analysis is performed online and feedback of performance is presented to the user. Mindswitch presents a basic 'on/off' switching option to the user, where selection of either state takes 1 min. Initial results show that fNIRS can support simple BCI functionality and shows much potential. Although performance may be currently inferior to many EEG systems, there is much scope for development particularly with more sophisticated signal processing and classification techniques. We hope that by presenting fNIRS as an accessible and affordable option, a new avenue of exploration will open within the BCI research community and stimulate further research in fNIRS-BCIs.

(Some figures in this article are in colour only in the electronic version)

Introduction

This paper describes principles, experiments and progress in harnessing simplified near-infrared spectroscopic systems as non-invasive instrumentation for brain–computer interfaces (BCIs). A BCI is a device that translates physiological measures of volitional thought processes into control signals capable of driving external computers, independent of the peripheral nervous system. Speed, accuracy, ease of use and length of training period are key criteria for assessing BCI innovations. Currently, no existing system performs well under all these headings [1] and consequently there is concerted research in developing new and alternative technologies for practical systems.

Near-infrared spectroscopy (NIRS) is a relatively new measurement modality that offers a portable, low-cost, sensitive option for BCI development. While still in its infancy in terms of BCI research, NIRS-derived optical responses have been demonstrated in a number of cognitive and motor task studies [2–4]. Such mental tasks are particularly suitable for BCI development. At present the measurement of electrical activity from the brain, using electroencephalography (EEG) or electrocorticography (ECoG), is the favoured method for harnessing such tasks for BCI development [1, 5–8].

Other functional imaging methods including fMRI and MEG have been demonstrated, but are relatively unsuitable due to the impracticalities of the equipment [9, 10]. Invasive procedures involving PET and SPECT are undesirable and not suitable for long-term use due to long time constants and the exposure to radioactive tracers. The use of functional near-infrared spectroscopy as demonstrated here offers an alternative investigation route. It is a safe, inexpensive and practical option for BCI signal acquisition, allowing for direct measurement of localized cognitive activity with minimal training. Its main drawback is the speed of operation which is limited due to the nature of the metabolic response responsible for the signal. Another important issue, as with most physiological monitoring, is ensuring good coupling when connecting the sensors to the body. A careful design of the optodes and coupling mechanisms is a critical factor as motion and obstruction of hair can severely affect performance and signal quality.

The principal contribution of this paper is the detailed exposition of a single site simplified real-time functional (NIRS) system as an instrument for BCI development. The suitability of our approach is demonstrated through the assessment of NIRS signal characteristics and detectable physiological effects that are suitable for BCI development [11, 12]. The system operates in a synchronous mode, i.e. the user is prompted for their input during defined time intervals. The results of preliminary trials are presented using a straightforward classification method for online analysis.

Methods

NIRS—the optical signal

An optical window exists (approximately 650–900 nm) where light is able to penetrate the outer tissues of the human head, including the cranium and the various meninges and fluids surrounding the brain. Light entering the head at a particular point becomes diffuse as the photons undergo multiple scattering events. A number of photons are absorbed while others continue to be scattered, following a random walk path movement through the medium. Some photons may be back reflected from tissue and exit the surface up to several centimetres from the original point source location. The amount of back-reflected photons depends on the optical properties of the tissue and may be detected using an appropriate optical source and a suitably placed photon detector. Both experimental and theoretical results suggest that photons collected carry information on optical properties and their changes at depths of up to approximately 2 cm in the adult human head [13], reaching the cortical surface. Changes in tissue oxygenation associated with brain activity modulate the absorption and scattering of these near-infrared (NIR) photons and hence affect the detected light levels emerging from the tissue (1–2% changes in signal amplitude) [14]. Measurement of light attenuation resulting from photon interactions is the basic principle underlying our approach. The attenuation due to absorption and scattering effects may be described by a modified version of the Beer–Lambert law:

$$A = \log_{10} \frac{I_o}{I} = \alpha c L B + G,$$

where A is attenuation, I_o is the incident light intensity (mW), I is the transmitted light intensity (mW), α is the specific extinction coefficient (mol^{-1} m^{-1}), c is the concentration of the absorber (mol), L is the distance between the source and the detector (m), B is the differential pathlength factor and G is a term to account for scattering losses.

The algorithm implemented by the optical BCI to calculate changes in haemoglobin levels is based on an algorithm described by Cope and Delpy [15] that relies on the modified Beer–Lambert law

$$\Delta A = (\alpha_{HbO} \Delta c_{HbO} + \alpha_{Hb} \Delta c_{Hb}) BL,$$

where ΔA is the change in light attenuation, α_{HbO} and α_{Hb} are the specific extinction coefficients of oxy-haemoglobin (HbO) and deoxy-haemoglobin (Hb), respectively, and Δc_{HbO} and Δc_{Hb} are the concentration changes in HbO and Hb, respectively.

The algorithm can be applied to multiple wavelengths of light; in this case, two are used. The two NIR light sources, at 760 nm and 880 nm, are chosen to be on either side of the isobestic point to evaluate the two chromophores of interest, i.e. Hb and HbO.

Various fNIRS imaging studies have reported optical responses due to motor, cognitive, visual and auditory functions [16], and in a previous study we reported an optical response due to motor imagery related to localized cerebral blood flow changes in the sensorimotor cortex [11]. Analysis of the signals showed characteristic changes in the deoxygenated and oxygenated haemoglobin concentrations during mental activation. Typically, an increase in oxy-haemoglobin (HbO) and a decrease in deoxy-haemoglobin (Hb) occur after the onset of movement execution or imagery. From our preliminary studies HbO concentration was found to exhibit a greater, more significant change during mental tasks. The optical BCI detects and characterizes changes in HbO in real time, giving user feedback, which could also be translated to control external devices.

Functional NIRS measurement and instrumentation

Functional NIRS measurements are made using one of the three methods, namely continuous wave (CW), time-resolved (TR) and frequency domain (FD). Each of these manifests specific strengths and weaknesses when considered in the light of a particular application. Broadly, time-resolved and frequency domain methods yield quantitative chromophore concentration measurements at the cost of increased apparatus complexity while CW methods in their most basic guise yield only qualitative information on such changes. This is because a direct measurement of photon pathlengths cannot be made, and therefore the differential pathlength factor must be estimated based on empirical studies. Time-resolved spectroscopy can gauge the pathlength by measuring the time taken for photons to traverse a medium, which is termed 'time of flight'. In the frequency domain approach, a light source is modulated at a very high frequency (hundreds of megahertz) and the light migrating through tissue undergoes both amplitude and phase shifts. The phase delay is related to the average time of flight of the photons, and the differential pathlength can be
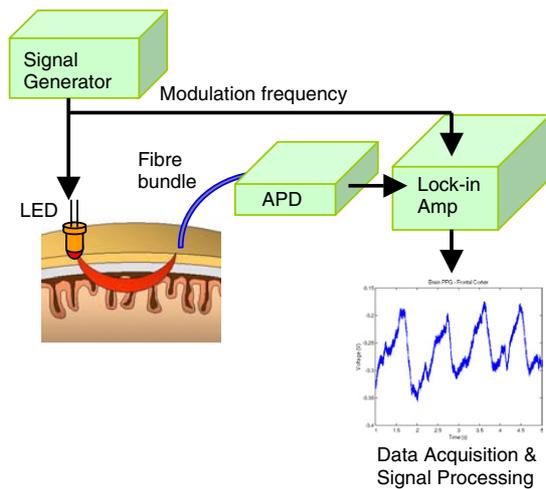
Figure 1. Components of a continuous wave NIR system.

calculated. Using CW a light source is switched on constantly, or modulated at low frequencies of a few kilohertz. Magnitude changes in the detected light signal are used to evaluate tissue attenuation. This can be implemented easily on account of its simplicity and flexibility and yields an inexpensive practical system. Further information on NIRS techniques, including an excellent introduction to NIRS instrumentation, is given by Rolfe [13]. As qualitative measurements are sufficient for detecting haemodynamics changes, the CW method was chosen for implementation in this BCI application.

Functional NIRS-BCI system design

The fundamental components of any fNIRS system are the light source and the detector although adequate care must also be taken in optode design, driving electronics, data acquisition and signal processing. The fNIRS system we have built for this study is shown in figure 1. Light emitting diodes (LEDs) at wavelengths of 760 nm and 880 nm are used (Opto-Diode Inc. APT-0010/OD-880F), each having a narrow beam angle of 8° and a spectral bandwidth at 50% of 30 nm and 80 nm respectively. These two wavelengths are chosen to allow blood oxygenation to be measured, as haemoglobin has different attenuation spectra depending on its oxygenation state. The LEDs emit a combined average power of less than 2 mW mm^{-2} and are modulated in the low kilohertz range. Given their small dimensions, the LEDs may be placed in direct contact with the scalp. The detector is an avalanche photodiode (APD), Hamamatsu C5460-01, which is connected 3–4 cm from the light source via a 3 mm diameter, 1 m long, fibre optic bundle. Lock-in amplifiers (Signal Recovery Model 7265) are used to identify each light source, while also reducing noise due to ambient light. The data are recorded at a sampling rate of 100 Hz by a 16 bit A/D data acquisition card, Keithley PCMCIA16AI.

Optode design and placement

A careful design must be applied to the mechanics of coupling light from the optical sources and detectors (optodes) to and from the subject's head. It is important to maintain a good connection with the scalp and also to push hair aside. Dark hair obstructing the photon's path can significantly attenuate the signal, and every effort must be made to overcome this problem; combing hair out of the way, fixing with hairgel and hair clips are an imperative part of the experimental regime. Although the fundamental method of connecting optodes to a subject's head may seem trivial, it seems to have the greatest bearing on the system performance as it has a great influence on the signal quality. A stable connection between the optodes and scalp is vital to ensure that the pathlength of the photons does not change and also to prevent ambient light saturating the detector. Such effects create spurious motion artefacts affecting the validity of the detected NIR signals. The challenge is to ensure rigid optode positioning while still allowing for subject comfort. Solutions to date include modified cycle helmets, thermoplastic moulded to the contours of each subject's head, spring-loaded fibres attached to semi-rigid plastic forms and fibres embedded in rubber forms [17]. Here an alternative approach was taken using a mechanical mounting structure to support the weight of the optodes while also cradling the subject's head, avoiding the effects of strain and discomfort that can occur with tight restrictive straps. The mechanical mounting system allows the person to sit comfortably, while a supporting structure is positioned about the person to hold the optodes in place. Mechanical supports for the optodes are connected to a seat with an adjustable back incline. This provides the option of conducting studies where the subject is supine, reducing certain physiological noise effects such as the Mayer wave [18]. This was shown for measurements taken from the same subject assuming different postural positions [3]. The mechanical framework is shown in figure 2(a). The position of the supporting structure can be altered by varying the height and also within the horizontal plane to allow for varying spinal curvatures, i.e. a subject's head sits more forward if there is a large curvature of his back. The framework allows optodes to be positioned over areas of the head that are generally of interest in functional brain imaging studies, e.g., visual and motor association areas. The physical framework consists of semicircular rails onto which optode holders can be attached and removed. The optode holders can slide along these rails and be secured into a required position. One of the semicircular rails curves above the left and right sensorimotor cortices, which provides good optode placement for investigating motor imagery [11].

In terms of optode placement, there is currently no standardized placement scheme for NIRS measurements. In order to be able to reproduce measurements from the same subjects and also to ensure consistency between studies, a well-defined method of performing physical measurements needs to be defined. This is especially important in the absence of fMRI information, where anatomical and functional details are available. As optical measurements are typically taken based on the measurements of the EEG 10-20 system we have proposed a type of polar coordinate system in terms of the 10-20 positions, where the optode position is described in terms of distance and angle with respect to a defined EEG 10-20 position. The nomenclature is as follows '10-20 position origin; distance from origin (angle wrt Cz)'. The origin is based
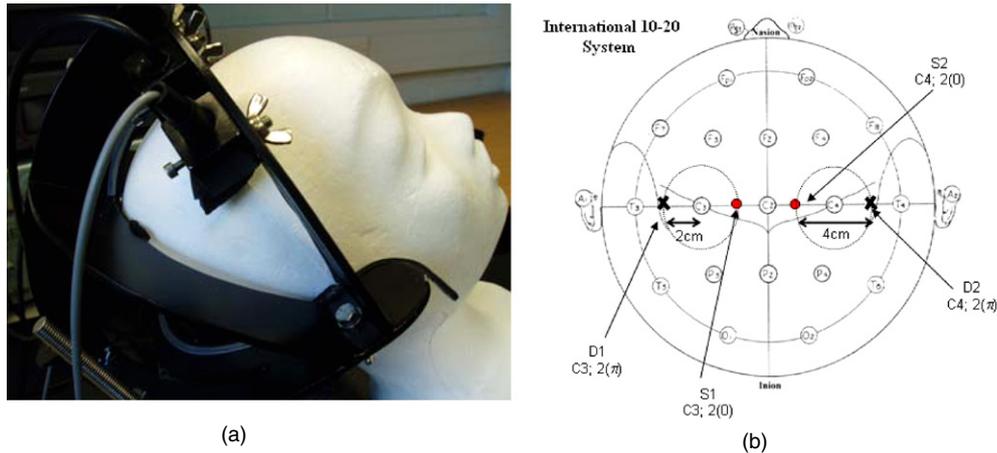
Figure 2. (a) Mechanical mounting system and (b) proposed optode placement system based on the conventional EEG 10-20 system.

on the closest 10-20 position and the vertex, i.e. Cz, is used as a general reference point to describe the placement angle. The positions of a source (S1) and detector (D1) placed 4 cm apart, lying 2 cm directly above and below C3 respectively, can be described by C3; 2(0) and C3; $2(\pi)$, as shown in figure 2(b). Similarly for optodes placed around C4, source (S2) and detector (D2) are placed at C4; 2(0) and C4; $2(\pi)$. Such a standardized placement scheme is important for concurrent measurements with other measurement technologies such as EEG.

Software

We have previously described the ability of our NIRS system to detect brain vascular dynamical changes associated with motor imagery [19]. Further work involving a number of preliminary brain–computer interface applications is described elsewhere [3]. Here, in the interests of brevity we choose to describe the experimental application which best epitomizes the principles underlying our fNIRS-based BCI. The simplest BCI requires a binary (yes/no) signal, which is achievable using a single-channel system. The optical response that is detected at the left or right motor cortex, due to imagined hand movement, may be used to provide this binary channel.

The goal of this experiment was to demonstrate a binary switching action controlled using mental imagery tasks—we refer to this paradigm as a 'Mindswitch'. The system operates in a synchronous mode, i.e. the system is active only during defined periods [20]. In this model, two options are presented to the user and highlighted in turn by the controlling software. When the user's desired target is highlighted, he/she performs imagery tasks to indicate his/her selection. The device monitors motor cortex activity during both options and then compares the response to each. The option associated with a larger change in HbO is used to assess the physiological response. The HbO signal was chosen for classification as this was noted to exhibit larger signal changes than Hb [3, 11].

Experimental procedure

Three healthy subjects (two right-handed and one left-handed, average age 35) participated in the evaluation of 'Mindswitch'.

Instruction given to user by means of small square (white or red)
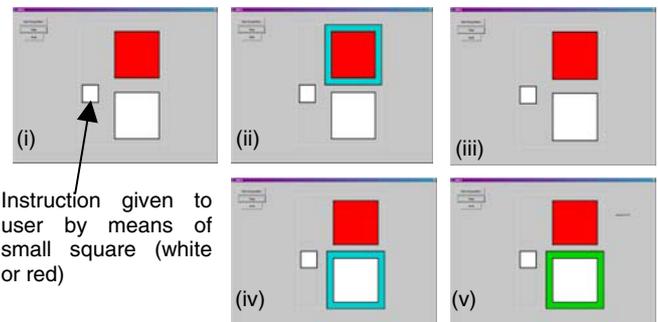
Figure 3. (i)–(v) Sequence of operations in Mindswitch.

Motor imagery was used as the mental strategy for controlling the application. Subjects resided comfortably in a supine position throughout the experimental trials and optodes were placed above the motor cortex at C3; 2(0) and C3; $2(\pi)$ for the right-handed subjects and C4; 2(0) and C4; $2(\pi)$ for the left-handed subjects. Subjects were instructed to imagine softly clenching a ball with their right hand, while their arms rested relaxed on the armrest. They were asked to imagine the kinaesthetic experience of movement while avoiding muscle tension [21].

Subject 2 and subject 3 each participated in one experimental session. To investigate performance over time, subject 1 participated in four experimental sessions spread over a week. Subjects 1 and 2 had participated previously in motor imagery experiments, while subject 3 received no prior training. Each session consisted of two experimental runs, with a break in between. During each experimental run, the subjects were asked to select a target ten times. Two target squares are presented to the user for selection—a red square and a white square. The sequence of procedures involved in choosing a target is shown in figure 3. Selection of a target takes a total duration of 1 min, and involves the following procedure.

(1) The first 15 s is a resting period, establishing a baseline condition. In the last 5 s of this period, a command is given to the user by means of a small coloured square indicating which target must be selected.
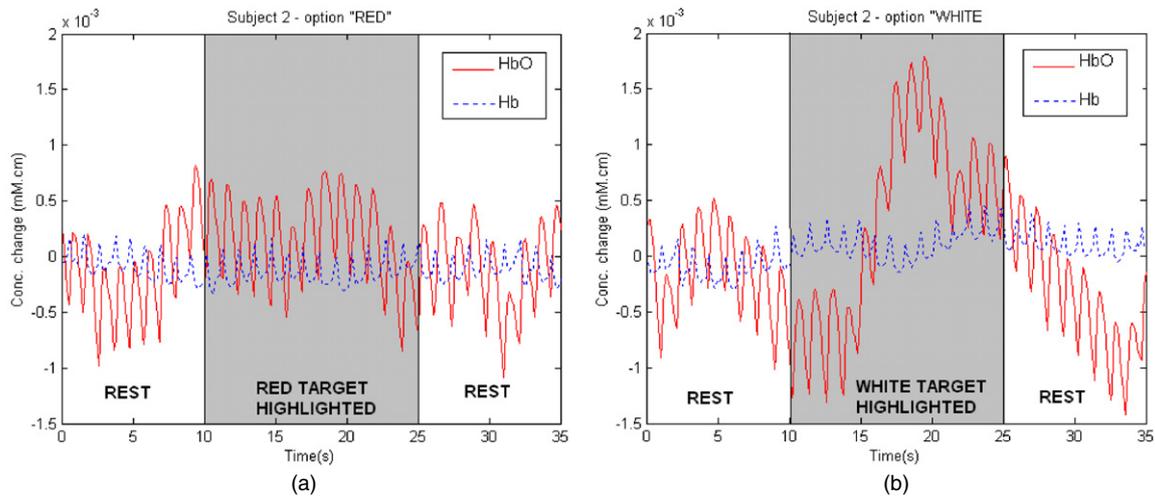
Figure 4. HbO/Hb response during a single trial (raw data): (a) when the red square option is highlighted, (b) when the white square option is highlighted. The average HbO signal is evaluated during each time interval and average HbO changes are evaluated for each option and compared. In this trial, the white option is selected.

(2) In the next 15 s the upper target, the red square, is highlighted. If the user wishes to select the highlighted target, he/she must perform imagery tasks during this time.

(3) The following 15 s is another rest state allowing the HbO signal to return to baseline if necessary.

(4) During the next 15 s the lower target is highlighted, and again the user may perform imagery if the highlighted target is desired.

(5) Rest follows, with the decision being presented to the user and the score updated (number of correct trials/total number of trials).

Data processing and classification

Signal processing and user feedback are performed online by the BCI. HbO concentration changes are evaluated from the detected light signal, based on the algorithm described by Cope [15]. The average HbO signal is evaluated during the last 10 s of the rest period and during the last 10 s of the target selection period. In this way, for each trial, the average HbO change is established for the red target and for the white target. A decision is made by the system based on which target elicited a larger HbO signal change. Figures 4(a) and (b) show the haemodynamic response for a single trial, and illustrate the time intervals used to evaluate HbO signal changes. The signals presented here are raw data. The oscillatory component is due to the cardiac cycle, to give an impression of the magnitude of the functional haemodynamic response. From these data it is clear that even before signal processing, a significant response can be observed by eye (only the algorithm to calculate Hb/HbO has been applied to the detected light signals). The Hb signal, also shown in figure 4, is not currently considered for classification by the BCI but we intend to investigate this response further. From these graphs, it is clear that the white square option causes a larger change in the HbO signal and is therefore selected. The decision is displayed to the user at the end of
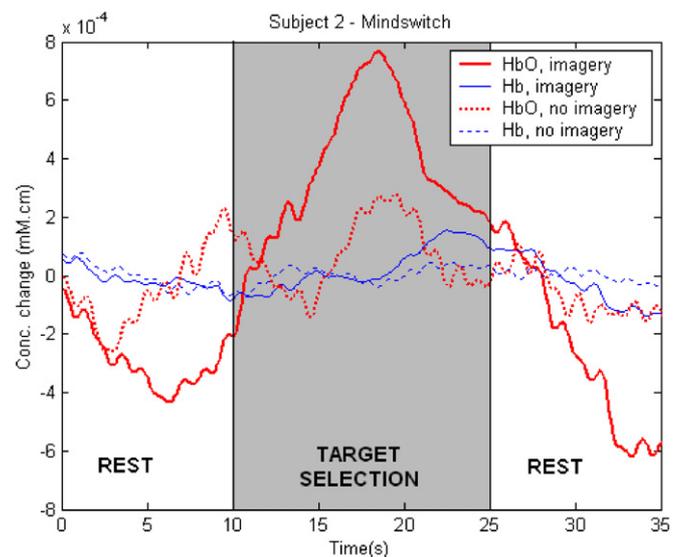
Figure 5. Subject 2—haemodynamic response measured at the right motor cortex during target selection trials. Signal has been low-pass filtered to reduce pulse artefact. Average response is shown for ten trials, i.e. one experimental run. The thicker line is the average of the ten imagery tasks and the thinner line the average of the ten epochs when no imagery was performed.

each trial and a score out of ten is updated on the visual display throughout the trials.

Results

Results are presented based on 60 trials for subject 1, 10 trials for subject 2 and 20 trials for subject 3. One session for subject 1 was rejected as the subject reported difficulty in performing imagery due to general fatigue, similarly for one experimental run for subject 2. The typical response for subject 2 for an experimental run of ten trials is shown in figure 5. The average response during ten motor imagery tasks is shown versus the average response during ten epochs of no

Table 1. Average HbO signal changes during fNIRS-BCI trials. Each experimental run consists of ten trials; there are four possible outcomes: (i) red square is targeted and selected (correct response), (ii) red square is targeted but white is selected (incorrect response), (iii) white is targeted and selected (correct response), (iv) white is targeted but red is selected (incorrect response). For each experimental run, the average response and standard derivations are given and the number of times of occurrence of each outcome.

		Red target red selected ✓	Red target white selected ×	White target white selected ✓	White target red selected ×	Accuracy
Subject 1	Avg.	0.74	–	0.40	0.33	90%
Exp. 1	St. Dev.	0.36	–	0.22	–	
	No. of trials	4	0	5	1	
Exp. 2	Avg.	0.62	0.39	0.41	–	80%
	St. Dev.	0.50	0.48	0.19	–	
	No. of trials	2	2	6	0	
Exp. 3	Avg.	0.41	–	0.52	0.57	80%
	St. Dev.	0.19	–	0.20	0.27	
	No. of trials	2	0	6	2	
Exp. 4	Avg.	0.24	0.22	0.34	0.22	70%
	St. Dev.	0.02	0.13	0.19	–	
	No. of trials	2	2	5	1	
Exp. 5	Avg.	0.08	0.22	0.34	0.22	70%
	St. Dev.	0.04	0.13	0.19	–	
	No. of trials	2	2	5	1	
Exp. 6	Avg.	0.79	–	0.22	0.01	80%
	St. Dev.	0.49	–	0.07	–	
	No. of trials	4	0	5	1	
Subject 2	Avg.	0.47	0.41	0.43	–	90%
Exp. 1	St. Dev.	0.40	–	0.29	–	
	No. of trials	3	1	6	0	
Subject 3	Avg.	0.35	0.25	0.16	0.17	70%
Exp. 1	St. Dev.	–	0.12	0.09	–	
	No. of trials	1	2	6	1	
Exp. 2	Avg.	1.11	–	0.66	0.67	90%
	St. Dev.	0.24	–	0.45	–	
	No. of trials	3	0	6	1	

imagery. There is a significant increase in HbO concentrations when imagery is performed. Table 1 presents the average response of each experimental run for each subject. Subject performance is evaluated simply by the ratio of the number of correct classifications to the number of trials. Subjects were able to achieve reasonable accuracy levels, with an average accuracy of 80%, and in the case of subject 1 performance was consistent throughout the week.

Discussion

The results as given are limited in what they can tell us about this particular instrument's competency as a general purpose BCI given the relatively limited testing. However, the results do demonstrate that this simple instrument allowed some degree of BCI operation with quite basic technology and additionally some insight was gained into general issues with such BCI paradigms.

The imagery tasks involved were straightforward concepts, although subjects reported the need to develop an individual strategy to perform mental imagery. This included the imagination of motor functions beyond hand movement,

e.g. pedalling a bicycle with one leg, kicking footballs and sifting one's fingers though a bucket of grain. The use of continuous feedback as explored in pilot studies [3] may be useful for helping users to cultivate such strategies. Feedback provided by the end result, as given by 'Mindswitch', has proved sufficient in EEG BCI systems; however continual feedback such as using virtual reality has been shown to improve task performance [22]. The benefit of increasing feedback to emphasize or impede the motor imagery process needs to be examined further. During rest intervals, envisaging concepts completely unrelated to movement was found to be difficult because motion is associated with so many phenomena [23]. Therefore, it may help to integrate some graphical representations for this purpose.

The overall system performance may be improved through a number of methods, including signal augmentation, signal classification and noise reduction. Information content may be enhanced by augmenting the signal with Hb concentration changes. The Hb level is the target parameter in fMRI studies and should yield additional features. The system configuration needs to be optimized to improve the integrity of the smaller Hb signal change, which is susceptible to cross-talk effects due to assumptions made in the modified Beer–Lambert law

algorithm. By choosing optimum wavelengths of light, the Hb signal integrity may be improved [24]. Addition of a third wavelength would also allow respiratory enzyme cytochrome oxidase concentration changes to be measured which are also linked with brain functional activity. This could then be used as an additional feature in event classification. An alternative approach to signal augmentation would be to develop a hybrid system by integrating other brain monitoring modalities, such as EEG, with the optimal deployment of NIR techniques. Optical signals are ideal for multi-modal studies, as the light signal does not interfere with electrical or magnetic fields.

Clearly, the switching process as demonstrated is slow as a result of the comparative approach based on a relative threshold. Some pilot studies [3] that we carried out used absolute thresholds, i.e. where classification of an event occurs if the change in the average HbO concentration exceeds a pre-defined reference level. This yielded faster speeds of operation, but at the cost of less flexibility and accuracy. Part of the reasoning behind the approach taken in Mindswitch was to facilitate greater flexibility, allowing easy accommodation of new users. A threshold does not need to be calculated for each user over numerous trials. Moreover, an ill-defined threshold or signal drift can lead to increased errors. However, in order to achieve faster information transfer rates, thresholding may be preferable. This may be combined with feature classification methods and asynchronous mode implementation. More sophisticated signal processing is required to prevent the occurrence of false positives due to physiological noise effects as we have discussed in a previous work [25]. Support vector machines and hidden Markov models have been demonstrated with off-line data [4], and show some promise.

Another factor affecting the signal integrity is the effect of superficial layers on the detected signal. These layers of tissue are assumed to have a constant attenuation effect on the light signal; however, there is a slight effect due to extracerebral signal components [26]. This can be minimized by using multiple source–detector arrangements with different inter-optode distances, which would result in different penetration depths, thereby isolating the effect of superficial layers of tissue.

One of the major limitations of fNIRS is the nature of the haemodynamic response which limits the information transfer rate given that vascular changes occur over a number of seconds. Multiple channels and additional mental tasks may be used to overcome this issue. Further investigation is needed into the variety of mental tasks that can be used as control channels. A recent fMRI study has used four different tasks to provide 2D cursor control [27]. The mental tasks were left- and right-hand movement imageries, mental calculation and mental speech generation. Such mental processes have been detected using NIRS techniques and could therefore be utilized [19, 28, 29].

Recent studies have reported fast optical signals that may correlate with the event-related potentials detected by EEG. The optical counterpart of EP has been termed the event-related optical signal (EROS) [30]. A recent study revealed an EROS, showing a response of the order of milliseconds, correlating to the frequency of hand movement [31]. To achieve optimum speed, acquiring the fast optical signal will be essential. However, currently thousands of averages are required for its successful acquisition and the signal is highly localized. For EROS to be practical for BCI deployment, more robust and reliable methods of measurement must first be accomplished.

While physiological noise effects and motion artefacts obviously create errors, the occurrence of subject error must also be taken into consideration. Subjects reported that a lack of concentration or momentary confusion during the tasks led to erroneous target selections.

Conclusions

We have shown how a simplified fNIRS device designed to detect haemodynamic responses arising from mental imagery processes can be used as a control channel for a computer application. The resulting 'Mindswitch', in a synchronous mode, uses a single channel placed on a region giving a pronounced optical response. This work demonstrates the suitability of an optical interrogation modality to provide a control input signal to a BCI. The advantages of optical systems include safety, accessibility and non-invasiveness. The cognitive processes detectable with NIRS allow straightforward mental tasks to be used in controlling the optical BCI. The ultimate potential of fNIRS-BCI is dependent on increasing throughput and accuracy to rates useful enough for their adaptation by their intended users. This may be done by integrating more control channels, by seeking a faster optical response correlated to neuronal activity [30, 31] or by the addition of complementary functional brain imaging modality. It is hoped that this work will foster further investigations into the application of NIRS signals for a new era of BCI development.

Acknowledgments

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