On the suitability of Near-Infrared Systems for Next Generation Brain Computer Interfaces

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Introduction

Since Near-Infrared Spectroscopy (NIRS) was first reported in 1977 by Jobsis[1] as a new "window" into the body, it has found many uses within the biomedical field. Single channel near-infrared systems are most commonly used in clinical surroundings for transcranial cerebral oximetry in neonatal care, hematoma detection, and stroke patient monitoring. In addition to its clinical uses, near-infrared functional brain imaging is possible by detecting changing properties of tissue absorption and scattering associated with cerebrovascular response which naturally is coupled to neural activity. The current on-going development of multi-channel NIR systems, i.e. diffuse optical tomography (DOT), typically for brain imaging and breast imaging, portray the potential of NIR techniques for imaging applications. Mathematical modeling, simulation and experimental studies [2] have investigated light interaction with tissue and have resulted in a growing understanding of photon path propagation through tissue.

Near-infrared light can penetrate 1-2cm beneath the skin's surface, which is deep enough to perform functional mapping of the cerebral cortex. Various studies have examined brain activity due to motor, cognitive, visual and auditory functions.[3,4,5,6,7] Due to the good temporal resolution of NIR techniques the vascular response, which is in the order or 5-8 sec, resulting from such activity can be continuously monitored in real-time. Recent studies have revealed a fast optical response on the order of milliseconds that is thought to be due to changes in scattering properties of firing neurons. This signal may correlate with evoked potentials commonly used in EEG analysis, and has been termed the Event Related Optical Signal [4].

Brain Computer Interfaces (BCI) provide users with an alternative output channel other than the normal output path of the brain, i.e. the efferent nervous system and muscles. The purpose of a BCI is to detect physiological signals from the brain, typically electrical signals resulting from neural firing, and use an algorithm to translate this signal in order to control an output device. Most of the current BCIs, which rely on the brain's electrical activity, use surface EEG signals but implanted electrodes are also used [8]. The user must then learn to control their brain's electrical signals in order to control the external device. Learning techniques to command brain activity that ordinarily may not be consciously controlled is extremely difficult and can take months of training. This can cause a great deal of frustration and sometimes abandonment of the device [9]. There is a need for a more accessible interface that uses a more direct measure of cognitive function in order to control an output device.

This paper looks at the potential of NIRS as a novel signal acquisition tool for BCI development. The optical response denoting functional brain activation can be used as an alternative to electrical signals, with the intention of a more practical, user-friendly BCI.

Method

EEG-based BCIs can use various signals as input. Current systems use visual evoked potentials (VEP), slow cortical potential, P300 evoked potentials and control of mu and beta rhythms, i.e. sensorimotor rhythms [10]. VEPs require control of eye movement, and therefore this type of BCI is not fully independent of the brain's normal output pathways. The typical set-up involves the user presented with a screen containing an array of symbols/letters that flash in sequence. The user must focus their gaze on the required symbol. When this symbol flashes it activates a VEP above the occipital cortex. BCIs that are totally independent of the motor pathways use slow cortical potentials, mu and beta rhythms [11]. Such physiological signals are associated with movement, and can be controlled using motor imagery. Imagination of hand or foot movement can be used to navigate a cursor within a 2-D plane. Another approach uses the P300 evoked response that is associated with the "oddball" paradigm. This doesn't require any initial training, the P300 response occurs above the parietal cortex when a desired choice is highlighted on a screen. Habituation is an issue with this approach when considering long-term use.

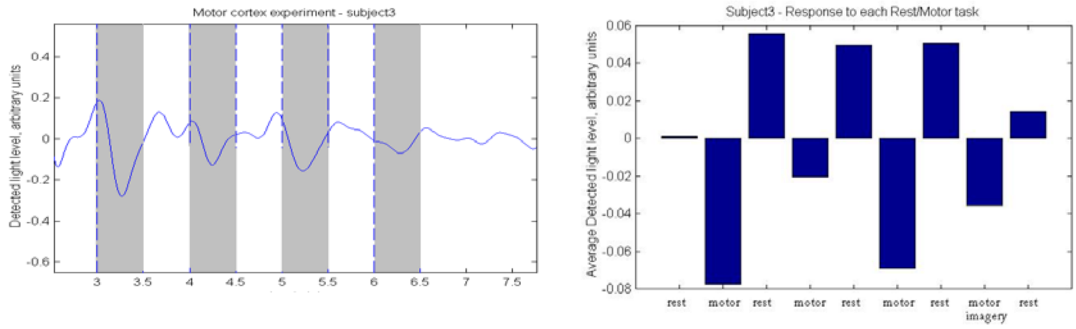
The simplest BCI requires a binary (yes/no) signal, which is achievable using a single-channel system. Optode placement and the protocol used to elicit the yes/no signal are user-dependent issues in terms of maximum signal strength, ease of use and accuracy. Motor imagery, i.e. the imagination of movement, is another possibility, and can be measured at C3/C4 of the 10-20 electrode placement system. Functional activation studies using NIR topographic techniques have detected responses due to motor activity. A peak response occurs after 5-8sec after the onset of movement [3]. A recent study revealed a fast optical signal, showing a response of the order of milliseconds, correlating to the frequency of hand movement [4]. It is known that motor imagery and real executed hand movement activate similar areas of the motor cortex. The authors recently conducted a study to investigate this response using NIRS. Motor imagery was found to give a similar optical response to actual executed movement. A single channel system was used for the study, and by differentiating between the optical response due to rest and the response due to motor imagery a simple BCI system can be developed.

	EEG	NIR
Spatial Resolution	Approx. 1cm	Approx. 1cm
Temporal resolution	Millisecond	Millisecond
Source of Signal	Post-Synaptic Potentials	Oxy-haemoglobin/Deoxyhaemoglobin concentration changes

Table1:- Comparison of EEG and NIR techniques

Results

Our single channel system has been used to investigate functional activation due to movement and also cognitive tasks. Hand movement, and imagined hand movement initiate neural activity within the motor cortex of the contra-lateral hemisphere. A few seconds after the onset of movement, due to a slow vascular response, a drop occurs in the light intensity received by the detector. Using a second channel above the motor cortex of the other cerebral hemisphere could then be used to detect left and right hand movement for possibly cursor control.



(a) (b)

Figure 1: Results of a motor task experiment, (a) first three shaded regions indicate actual hand movement, fourth shaded region indicate visualization of hand movement, (b) average of rest/motor epochs

Problem solving activates the frontal lobes. Concentration and memory related tasks can be used to control the signal received across the frontal cortex. Again, this is a signal that, with the aid of biofeedback, a user could learn to control quite easily. Habituation may be a problem with this approach, however as yet no studies have confirmed such an effect.

Event related optical responses correlated with the EEG evoked responses have been reported recently [6,7]. Event-related auditory oddball experiments, which produce the conventional EEG P300 response, result in optical responses using NIR topography that are consistent with fMRI studies[7]. In some current EEG based BCIs, the P300 signal is used. Although the timecourse of the EEG signal is much smaller, 300ms, compared to the optical signal, 5.8+/-0.3s [7], the latter technique required considerable averaging.

The fast optical signal is a relatively new development. Unlike the slow vascular response, the fast signal is thought to be due to changes in scattering properties of neuronal membranes as they fire. Fast neuronal signals in the motor cortex have been reported [4], although there is a need for greater investigation into this area[6].

Discussion

A simple BCI system can be developed using the optical responses from motor imagery or problem solving as input signals. Although the slow vascular response would mean a low information transfer rate, such signals are not difficult to control. In order to improve speed, acquiring the fast optical signal, and attaining an evoked optical response, will be the next step.

Conclusions

Speed, accuracy, ease of use and length of training period are the key criteria for BCI development. Currently no BCI performs well in all these aspects [8]. Greater accuracy rates and speed are needed particularly for neuroprosthesis control. Ease of use and training periods must be addressed in order for BCIs to be successful in terms of accessibility. A lot of the current BCIs require the user to learn a new thought process, which requires immense effort and can lead to frustration. In order to further BCI development, signal acquisition, signal processing and translation algorithms need to be addressed. This paper demonstrates the suitability of NIRS to detect changes in physiological signals, detected non-invasively, in order to control a BCI. The thought processes required are relatively straightforward and are a more direct measure of cognitive function. Our current work has used a single-channel, single-wavelength system in order to examine the feasibility of the concept. The next step will be to evolve to a dual-wavelength system to identify haemoglobin concentrations, and consider multiple channels to improve spatial resolution.

Although spatial resolution of NIR topography is poor, integration with other imaging techniques such as EEG and fMRI, optimum optode placement for maximum signal strengths can be achieved. Multi-modal BCI systems using NIR combined with EEG to integrate both systems' strengths may enhance performance. In order to progress with optical BCI development, further investigation is required in modelling light transport through the head to find optimum optode geometries, light emission powers and modulation frequencies. Instrumentation design follows from this, and must be adapted to achieve high signal to noise ratios and good temporal resolution in order to acquire the "fast signal" for optical evoked responses. Acquisition of such optical responses should bring NIR techniques to the forefront of BCI development.

An optical approach avoids noise issues associated with electrical signals. Optical techniques have various safety benefits - the user is isolated from electrical signals, NIR light is non-ionizing and is therefore suitable for long-term use, and the technique used takes a completely non-invasive approach. As with NIRS bedside-monitoring apparatus, NIR techniques offer the promise of a non-invasive brain-computer interface system that is portable, cost-effective, practical and above all safe.

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