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Classification of functional near-infrared spectroscopy signals corresponding to the right- and left-wrist motor imagery for development of a brain–computer interface

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HIGHLIGHTS

- Classification of fNIRS signals corresponding to the right- and left-wrist motor imagery.
- Hemodynamic responses of the right-wrist imagery are distinguishable from those of left.
- Signal slope improves the classification accuracy significantly than signal mean.
- Enhanced performance on examination of subset of the response data.

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ABSTRACT

This paper presents a study on functional near-infrared spectroscopy (fNIRS) indicating that the hemodynamic responses of the right- and left-wrist motor imageries have distinct patterns that can be classified using a linear classifier for the purpose of developing a brain–computer interface (BCI). Ten healthy participants were instructed to imagine kinesthetically the right- or left-wrist flexion indicated on a computer screen. Signals from the right and left primary motor cortices were acquired simultaneously using a multi-channel continuous-wave fNIRS system. Using two distinct features (the mean and the slope of change in the oxygenated hemoglobin concentration), the linear discriminant analysis classifier was used to classify the right- and left-wrist motor imageries resulting in average classification accuracies of 73.35% and 83.0%, respectively, during the 10 s task period. Moreover, when the analysis time was confined to the 2–7 s span within the overall 10 s task period, the average classification accuracies were improved to 77.56% and 87.28%, respectively. These results demonstrate the feasibility of an fNIRS-based BCI and the enhanced performance of the classifier by removing the initial 2 s span and/or the time span after the peak value.

1. Introduction

A brain–computer interface (BCI) provides a means of controlling machines and robots for locked-in people by interpreting the neuronal signals from the brain directly and bypassing the signals from the peripheral nerves and muscles [34]. Recently, researchers successfully trained people with head-implanted microelectrodes to control robotic and prosthetic arms [10]. Noninvasive methods, however, are preferable to avoid the inherent medical risks in microelectrode implantation. Various noninvasive modalities including electroencephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), and functional near-infrared spectroscopy (fNIRS) are currently being used to acquire brain signals for BCI applications.

fNIRS is a novel brain imaging technology that is used to measure the hemodynamic response of the cerebral cortex using near-infrared (NI) light (650–1.000 nm) [11,35]. The fNIRS technique is based on the measurement of hemodynamic changes in the cerebral blood flow, that is, the concentration changes of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR). fNIRS employs multiple emitter/detector pairs of NI lights operating at two or more different wavelengths. The lights emitted into the scalp diffuse through the brain tissues due to multiple scattering of photons. While the majority of the lights are absorbed in the tissues or continue to scatter, a portion of lights exit the scalp after passing through the cortical area, wherein the HbO and HbR chromophores in the path absorb them with different absorption coefficients. The

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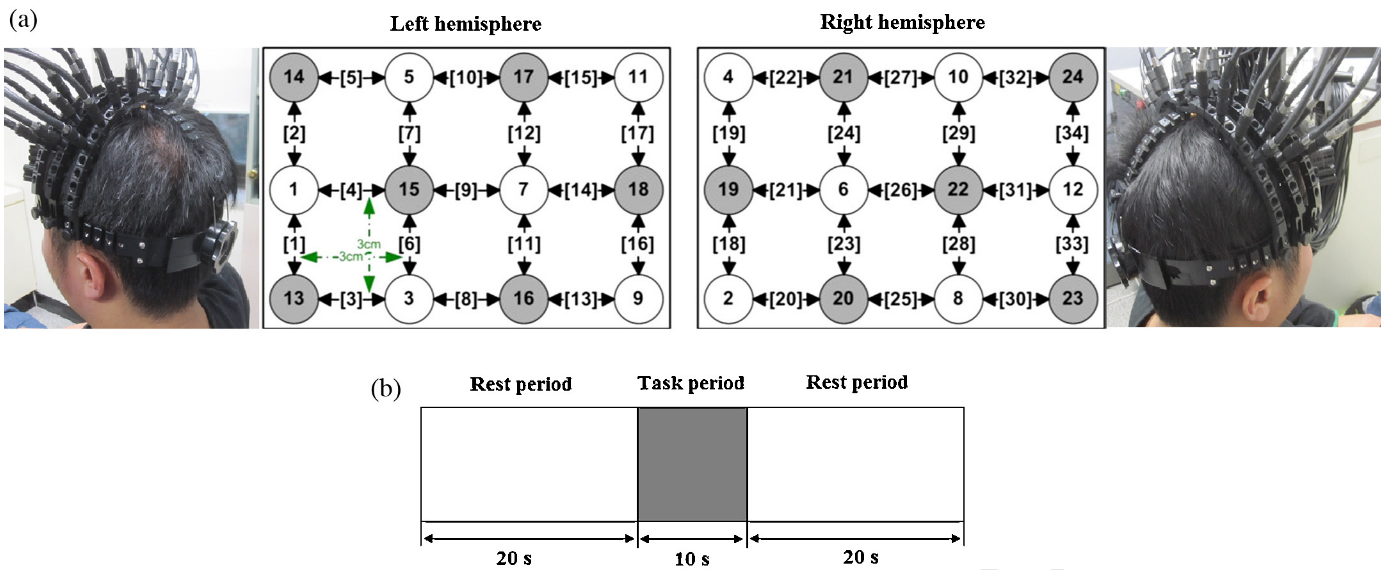

Fig. 1. (a) Optode placement and channel configuration: Each gray-filled circle represents an emitter, and each unfilled circle represents a detector. (b) Schematic illustration of the experimental paradigm used: The white blocks represent the 20 s rest periods at the beginning and at the end; the gray-filled block represents the 10 s task period.

exited photons are detected using strategically positioned detectors, and the intensity of the detected light is then used to calculate the HbO and HbR concentration changes (ΔHbO and ΔHbR) along the photon path. The principle of fNIRS measurement, first reported by Jobsis [16], has been applied to the study of cerebral hemodynamics for more than two decades, even though its use in brain mapping, brain-state decoding, and BCI is only a few years old [1,2,5,6,12–15,17,21,26,27,30,31]. The major advantages of fNIRS are its noninvasiveness, relatively low cost, portability, and wearability. Since fNIRS is an optical modality, its measurements are not susceptible to electrogenic artifacts [20].

In the present research, the adopted brain signal generation paradigm is motor imagery. Motor imagery can be defined as the mental rehearsal of motor acts that is not accompanied by overt body movements. It is a mental task often employed for BCI applications, and has been shown to work well in previous EEG-based BCI studies [23,24,29,33]. Indeed, Beisteiner et al. [3] demonstrated that the brain activation during a motor imagery is similar to the brain activation during the associated motor execution (overt body movement). Motor imagery tasks should be easy to learn and execute and, moreover, the use-friendliness of the BCI system is important. Motor imagery signal decoding, besides its significance to BCI development, is appealing from the prospective of neurorehabilitation.

In this study, by classifying the right- and left-wrist motor imagery signals, we achieved a significant advance towards an fNIRS-based BCI. After acquiring the fNIRS signals representing the right- and left-wrist motor imageries from the primary motor cortex, those signals were normalized and filtered. By using two distinct features (the mean and the slope of the signal), they were classified into two classes, "right-wrist motor imagery" and "left-wrist motor imagery." The average classification accuracy was as high as 87.28%. The contributions of this study are as follows: (i) To the best of the authors' knowledge, this is the first work on the classification of fNIRS signals corresponding to the right- and left-wrist motor imageries; (ii) it has been illustrated that the signal slope (SS), as a classification feature, offers significantly better classification accuracy than the signal mean (SM); (iii) it is found that the classifier performance can be enhanced when the analysis is performed on the focused time period, for instance, during 2–7 s time interval instead of the overall 10 s task period.

2. Experimental procedure

2.1. Participants

A total of 10 healthy adults were recruited (all male, right handed, mean age: 28.5 ± 4.8). Only right handed participants were sought, so as to minimize any variations in the hemodynamic responses due to the hemispheric-dominance difference. None of the participants had a history of any psychiatric, neurological or visual disorder. All of them had normal or corrected-to-normal vision, and all provided a verbal consent after they were informed in detail about the experimental procedure. The experiment was conducted in accordance with the latest Declaration of Helsinki.

2.2. Optode placement and channel configuration

Since motor imagery activates the brain's primary motor cortex [3,25], a total of 12 NI light emitters and 12 detectors were positioned over the left and right hemispheres to measure the signals from the left and right primary motor cortices. With the optodes configuration in Fig. 1(a), 17 interconnecting channels were made on each hemisphere by considering the imaging depth related to the emitter–detector distance [7–9,19,22]. For measurement of signals from the cortical area, an approximately 30 mm emitter–detector distance has been set [7]. Channels covering an emitter–detector distance of more than 30 mm were discarded, as it is not certain whether the signals received at such channels were through the cortical area or not and in any case the signal might be too weak to be used [9].

2.3. Experimental protocol

Each participant was seated in a comfortable chair facing a 15.6 in. monitor situated at a distance of 65–70 cm in a dimly lighted room. He was asked to relax for at least 5 min prior to the experiment in order to settle his heart rate and blood pressure down and to remain relaxed through the experiment so as to avoid, to the extent possible, any unnecessary movement or thinking. In each trial during the experiment, the first 20 s was a rest period to set up the baseline, followed by a 10 s task period, which was followed in turn by another 20 s rest period, for a total trial duration of 50 s.

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