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NSR 3914 1–10

ARTICLE IN PRESS

Neuroscience Research xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Neuroscience Research

journal homepage: www.elsevier.com/locate/neures

An online three-class Transcranial Doppler ultrasound brain computer interface

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ARTICLE INFO

Article history:
Received 10 October 2015
Received in revised form
20 December 2015
Accepted 25 December 2015
Available online xxx

Keywords:
Transcranial Doppler ultrasound
Brain computer interface
Spatial task
Motor imagery task
Lateralization
Online

ABSTRACT

Brain computer interfaces (BCI) can provide communication opportunities for individuals with severe motor disabilities. Transcranial Doppler ultrasound (TCD) measures cerebral blood flow velocities and can be used to develop a BCI. A previously implemented TCD BCI system used verbal and spatial tasks as control signals; however, the spatial task involved a visual cue that awkwardly diverted the user's attention away from the communication interface. Therefore, vision-independent right-lateralized tasks were investigated. Using a bilateral TCD BCI, ten participants controlled online, an on-screen keyboard using a left-lateralized task (verbal fluency), a right-lateralized task (fist motor imagery or 3D-shape tracing), and unconstrained rest. 3D-shape tracing was generally more discernible from other tasks than was fist motor imagery. Verbal fluency, 3D-shape tracing and unconstrained rest were distinguished from each other using a linear discriminant classifier, achieving a mean agreement of $\kappa = 0.43 \pm 0.17$. These rates are comparable to the best offline three-class TCD BCI accuracies reported thus far. The online communication system achieved a mean information transfer rate (ITR) of 1.08 ± 0.69 bits/min with values reaching up to 2.46 bits/min, thereby exceeding the ITR of previous online TCD BCIs. These findings demonstrate the potential of a three-class online TCD BCI that does not require visual task cues.

1. Introduction

Individuals who present as locked-in are unable to communicate verbally or gesture motorically but still retain cognitive functions. Many adults and children with severe and multiple disabilities, while not formally diagnosed as locked-in, do not have functional speech or any controlled motor abilities that allows them to communicate their more basic needs. In this sense, these young people share the complex communication needs of patients with locked-in syndrome (LIS). Brain computer interfaces (BCI) have been developed to provide communication abilities for patients with LIS or LIS-like impairments, with the aim of improving autonomy and quality of life (Wolpaw, 2013).

Brain computer interfaces allow the user to interact with their surroundings using real-time measures of brain activity. BCIs can be deployed for answering 'yes' and 'no' questions, environmental control (i.e. temperature or lights), speech generation, basic word-processing, and control of neural prostheses. There are many different technologies for measuring brain activity, including electroencephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), near infrared spectroscopy imaging (NIRS), and positron emission topography (PET). MEG, fMRI and PET are not suitable for everyday use due to the high cost and limited real-time capabilities (Wolpaw, 2013). Many studies have investigated EEG BCIs due to its high temporal resolution. However, EEG signal quality is heavily affected by noise from the environment and electrical artifacts (Nicolas-Alonso and Gomez-Gil, 2012). NIRS measures changes in blood hemoglobin concentration and is being investigated increasingly as a BCI modality since it is not susceptible to electrophysiological artifacts (Power et al., 2012). Transcranial Doppler (TCD) ultrasound is a non-invasive neuro-imaging technique used to assess the velocity of blood flow through major cerebral arteries. In comparison to other BCI technology, TCD is portable, lightweight, relatively inexpensive, robust to environmental/electrical artifacts, and has good temporal resolution (Badcock et al., 2012; Myrden et al., 2012). TCD, however, requires a trained individual to be able to find the optimal signal (e.g. highest signal-to-noise ratio when blood flow is in the

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http://dx.doi.org/10.1016/j.neures.2015.12.013

Please cite this article in press as: Goyal, A., et al., An online three-class Transcranial Doppler ultrasound brain computer interface. Neurosci. Res. (2015), http://dx.doi.org/10.1016/j.neures.2015.12.013

desired direction at the expected insonation depth). The insonation window may also be difficult to locate, especially in older adults (Stroobant and Vingerhoets, 2000), nonetheless, helmets can be fashioned and customized to allow for prolonged measurement (Bondar et al., 1990, 1991, 1994).

In comparison to a resting state, cognitive activity elicits an increase in cerebral blood flow velocity (CBFV) in the left and right middle cerebral arteries, which can be measured using TCD (Stroobant and Vingerhoets, 2000). Cognitive tasks can be used to control a BCI if they elicit changes in CBFVs that are discernible from those at rest. Lateralization of brain function refers to the preferential increase in blood flow to one hemisphere over another while performing a particular task or function (Gur and Reivich, 1980). In right-handed individuals, studies have shown that verbal tasks induce left hemispheric lateralization while visuospatial tasks result in right hemispheric lateralization (Gur et al., 1994; Myrden et al., 2011). The most commonly used verbal task for significant left lateralization is the word generation task in which the participant silently thinks of as many words as possible that start with a given letter (Silvestrini et al., 1994; Knecht et al., 1998a,b). Visuospatial tasks include mentally manipulating 2D or 3D shapes, and estimating depth or distance (Harders et al., 1989; Vingerhoets and Stroobant, 1999a,b). Studies have investigated other types of tasks that result in significant right side lateralization, such as left-side motor activation (Orlandi and Murri, 1996), visual-imaging (Silvestrini et al., 1994), or visuospatial working memory (Cupini et al., 1996) tasks.

To date, only a handful of studies have investigated the use of TCD as a BCI modality. In Myrden et al. (2011), participants were asked to alternate at 45 s intervals among a word generation task for left brain lateralization, a visuospatial (mental rotation) task for right-side lateralization, and a rest period in which the participant's mind was allowed to wander freely. For the mental rotation task, participants were shown images of a shape along with four other geometric figures, and were asked to identify the rotated version of the original shape. Using linear discriminant analysis (LDA), the authors differentiated between the performance of the word generation task and rest, and between mental rotation and rest, achieving accuracies from 80% to 85% (Myrden et al., 2011). However, lengthy task durations were required, limiting the data transmission rate. In a follow-up study using a three-class LDA, Myrden et al. (2012) varied the amount of time needed for the tasks, reporting that accuracies in excess of 70% could be attained with approximately 18 s task durations.

Subsequently, Aleem and Chau (2013) proposed a user-independent TCD BCI. Each participant performed the word generation, mental rotation, and baseline counting tasks. A classification algorithm developed from a single participant was then used to classify TCD signals from all other participants, reaching accuracies of 74.6 ± 12.6% (Aleem and Chau, 2013). Building on these early studies, Faress and Chau (2013) combined near-infrared spectroscopy and TCD into a hybrid binary (verbal fluency versus rest) BCI, and attained higher classification accuracies (86.5 ± 6.0%) than that achievable with either modality alone. Nonetheless, the hybrid BCI necessitated cumbersome set-up and specialized headgear. With a focus on functional application, Lu et al. (2014) designed an online TCD BCI speller, boasting an average specificity and sensitivity of 81.44 ± 8.35% and 82.3 ± 7.39%, respectively. While the BCI differentiated between rest and the simultaneous performance of mental spelling and imagined right-handed writing of the target word, a very modest average information transfer rate of 0.87 bits/min was reported (Lu et al., 2014). The most recent TCD BCI contributions have focused on advancing machine classification of blood flow velocities. Faulkner et al. (2015) proposed sequential hypothesis testing as an alternative to discriminative classifiers, discerning between counting and verbal fluency using a mean task

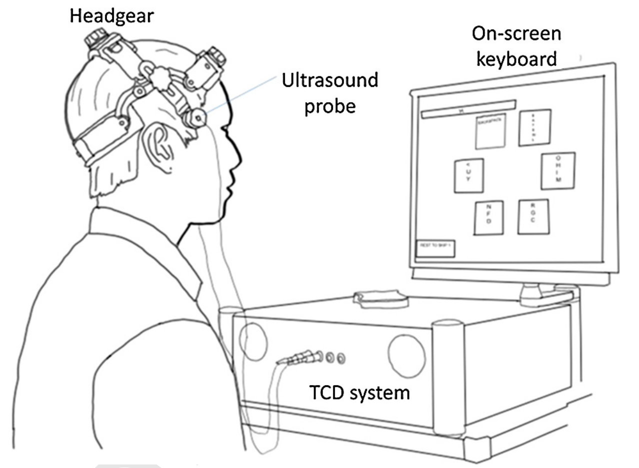

Fig. 1. Experimental setup.

duration of 23 s and yielding an accuracy of 72%. Lu et al. (2015) investigated different feature selection and binary classification approaches to maximize accuracy while minimizing computational complexity. The combination of weighted sequential forward selection and a support vector machine yielded 87.6 ± 3.27% accuracy with very simple time domain features (Lu et al., 2015).

Although previous TCD BCI studies have used mental rotation as the visuospatial task, a visual prompt has been required, which precludes self-paced control and excludes usage by individuals with concomitant motor and cortical vision impairments (Mason and Birch, 2003). Thus, in this study, we investigated right-side, vision-independent activation tasks for a three-class online BCI.

2. Methods

2.1. Participants

Eleven participants without disabilities between 18 and 40 years of age were recruited. The inclusion criteria for participants were: normal or corrected-to-normal vision, minimum grade six English literacy level, and no known history of metabolic, cardiovascular, respiratory, psychiatric, psychological, or drug/alcohol related conditions. One of the participants could not be scheduled for the last two sessions and was thus excluded. The remaining 10 participants (three male, mean age = 26.2 ± 3.3 years) were all right-handed as quantified by the Edinburgh Handedness Inventory (mean score of 79.4 ± 20.2). Written informed consent was obtained from each participant. The study was approved by the Research Ethics Boards of both Holland Bloorview Kids Rehabilitation Hospital and the University of Toronto.

2.2. Instrumentation

To measure the real time spectra of blood flowing through the left and right middle cerebral arteries (MCA), the MultiDop X-4 TCD (Compumedics Germany GmbH in Singen, Germany) system and headgear with two fixed ultrasound probes were used (Fig. 1). The probes operate in pulsed-wave (PW) mode at 2 MHz. The data were recorded at a sampling frequency of 100 Hz.

The MCA was insonated in accordance with the method of Alexandrov et al. (2007). Ultrasound gel was applied between the probe and skin to maximize signal transmittance. The probe was placed on the transtemporal window with an initial depth set to 50 mm. The insonation angle and depth were then adjusted until the MCA and anterior cerebral artery bifurcation was found. The depth was reduced until maximum unidirectional flow toward the

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