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Functional connectivity of the PFC via partial correlation

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ABSTRACT

Functional near-infrared spectroscopy (fNIRS) has been applied to study of brain oxygenation and metabolism. In this study, we aimed to investigate the partial correlation (PC) in fNIRS signals on functional connectivity in the prefrontal cortex (PFC) during a modified version of the color-word matching Stroop task. A continuous wave 16 channels near-infrared spectroscopy device (ARGES Cerebro, Hemosoft Inc., Turkey) was used to measure the changes in HbO2 and Hb concentrations from 12 healthy volunteers. Partial correlation (PC) values were computed for each stimulus condition. The results of ANOVA test ($p < 0.05$) in HbO2 and Hb signals indicate the bilateral connections between two brain hemispheres. The partial correlation analysis, by removing the common effect of channel interference, offers a suitable measure to evaluate the performance of the prefrontal cortex. Also, the results of partial correlation showed that compared to Hb signal, HbO2 signal is more sensitive to brain activities. This study suggests that fNIRS is a valuable tool for demonstrating the relationship between cortical function in complex cognitive activities.

1. Introduction

In addition to techniques such as positron emission tomography (PET), diffusion tensor imaging (DTI), electroencephalography (EEG), magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) which have been employed since 90s, fNIRS as a non-invasive technology monitors brain activation through direct measurement of cerebral hemodynamic response. This method is favored and considered by researchers [1,2].

The fNIRS technique has advantages over other imaging techniques such as fMRI including less restrictions on the subject's movement, portability, low cost, proper time resolution and simultaneous measurement of oxy-hemoglobin (HbO2) and deoxy-hemoglobin (Hb). On the other hand, it is characterized by some limitations in terms of penetration depth and low spatial resolution [1,3–5].

Generally, it has been shown that during cognitive activity [6] or resting state [7], different areas of the brain are linked to each other. The relation is called functional connectivity which is not based on an anatomical connectivity but it is relies on temporal correlation between the spatial distribution of neurophysiological events or synchronization of spontaneous neural activity in the absence of an external stimulus [7,8]. Accordingly, there are certain regions of the brain that not only perform their own specific tasks, but also share their information with other brain regions. Thus, a study of brain function can help explore integration, organization and architecture of the brain network [5].

A proper tool to measure functional connectivity is fNIRS [9] as it has a couple of features such as non-invasiveness, unobtrusiveness during cognitive tasks, prompt and convenient application. Given its wide application in cognitive tasks, its validity has been evaluated in several studies along with a discussion of its limitations in other studies.

Several recent studies have been done to investigate brain functional connectivity in resting state on the adults [10–16] and infants during sleeping using hemodynamic signals [17]. Furthermore, among functional connectivity studies that are underpinned by cognitive activities in the presence of an external stimulus, such as color-word matching Stroop task [18–20], verbal fluency task [5],

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language paradigms [21], Go/NoGo task [22,23] and N-back task [24,25] can be mentioned.

Previous studies have demonstrated that during complex cognitive task [18–20,26], the prefrontal cortex (PFC) is activated as a result of executive functions in the brain. Executive functions consist of a group of cognitive operations such as relevant information, ignore distracting information, conflict resolution and selection of proper response [27]. One of the tasks which widely have been used to overcome conflict in investigating of PFC activity is color-word matching Stroop task [28,29]. In each stimulus of Stroop task, two types of information are provided. One of them is related to the meaning of the word and another is the recognition of word color. To perform task, the person who is trained to give the behavioral response based on one type of information and ignore the other one.

In this study, fNIRS signals are recorded from forehead and color-word matching Stroop task is used to active the PFC. Up to now, a variety of different criteria such as correlation [5,11,13,30–32], cross-coherence [10,33], mutual information [34–36], wavelet transform coherence (WTC) [19,20,24,37], partial coherence [23,33,34] and partial mutual information [34] are used to study brain functional connectivity in the both fNIRS or fMRI imaging systems. In many of fMRI studies, partial correlation is considered and used as suitable criterion for investigation and understanding of brain functional connectivity [38–41]. Since both fMRI and fNIRS systems rely on the oxygen concentration variations in neurovascular activities, it is reasonable to employ this criterion in fNIRS signals. This study is the first to use partial correlation to examine functional connectivity in the PFC during a complicated cognitive activity.

2. Materials and methods

2.1. Subjects

fNIRS signal were recorded through 12 adult volunteers (7 male and 5 female) ages 20 up to 31 (mean 26.2 and SD 4.3). The subjects who participated in this study were right-handed, healthy without any neurological, medical and psychiatric disorders. All of the participants had normal eyesight and normal color vision. Written informed consent was obtained from all of them before fNIRS monitoring.

2.2. fNIRS data acquisitions

We used fNIRS device (ARGES Cerebro, Hemosoft Inc., Turkey) to record concentration changes of the oxy-hemoglobin ($\Delta[HbO_2]$) and deoxy-hemoglobin ($\Delta[Hb]$). This device was developed at the Neuro-Optical Imaging Laboratory of Bogazici University in collaboration with the Hemosoft Inc and is a continuous wave dual wavelength fNIRS system with 16 channels.

Our device contains a flexible probe which is placed on forehead. The probe has four LED light sources and ten photodetectors. It has sixteen source detector pairs with an equal distance of 2.5 cm, monitoring the region of the prefrontal cortex (PFC) underlying the forehead [18,26]. The sampling rate of device is 1.7 Hz. The probe position (the light sources and detectors) on forehead and location of the channels are shown in Fig. 1.

HbO2 and Hb concentration changes have been calculated by the modified Beer–Lambert Law [42–45]. Previous studies have shown that neuronal activation lead to sequential changes in the HbO2 and Hb concentrations.

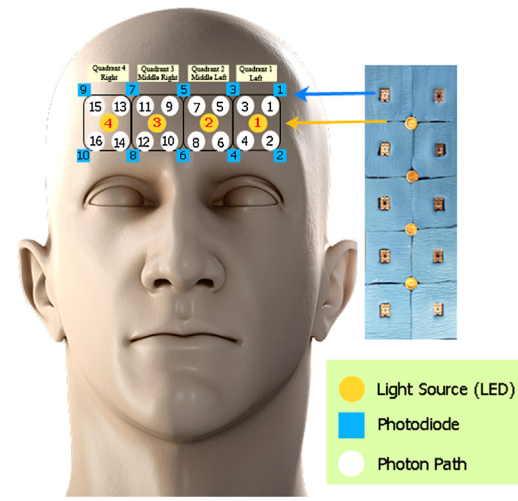

Fig. 1. Presentation of fNIRS probe and the location of the sources and detectors on the forehead with their channels. Yellow circles are the sources and detectors are blue squares. White circle identifies the location of the channels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Experimental procedure

We used the computerized version of the color-word matching Stroop Task with a block design and where the words were in Turkish language [18,26].

In this task, two rows of words appeared on the monitor on a black background. The word of the top line was printed in an ink color whereas other word in the bottom line was white. The subjects should recognize that if the color of the word in upper line matches with meaning of the word in lower line or not? If color of the ink and name of the color match together, then the subject was to press on the left mouse button with her/his forefinger and if not, middle finger presses on right mouse button. Subjects were told to do the task quickly and correctly as possible. Stimuli in Stroop task divide to three stimulus conditions that these are neutral (N), congruent (C) and incongruent (I). During neutral stimulus, in upper line, 'XXXX' letters was displayed with one of these colors red, green, blue or yellow, and in lower line, there was one of the following words "red", "green", "blue" or "yellow". In the congruent stimulus, upper line contained one word like red, green, blue or yellow with same color of its meaning. In the incongruent stimulus, the color of words in upper line was different from their meaning (e.g., the "green" was displayed with red color). In order to prevent participants from focusing on the lower word, the upper word was presented 100 ms before than lower word. Therefore, visual attention of subject is shifted to the top word. The experiment contains a total of 15 stimuli blocks (five blocks of neutral, congruent and incongruent stimuli), but the arrangements of each stimuli block was random. Each block consisted of six trials distributed homogeneously. In each stimulus condition, the number of "yes" trial and "no" trial was the same. The words remained on the screen until subject is pressed button in the maximum time of 3 s. Interstimulus intervals within each block was 4.5 s. Thus, each block lasted 27 s and time interval between each block was 20 s. The distance among subject and monitor was 0.5 m. Experiments were performed in a silent, lightly dimmed room. The task protocol is approved by the Ethics Review Board of Bogazici University [26]. Fig. 2 is shown an example of color word Stroop task in Turkish language. The corresponding of this question "Does the color of the upper word correspond with the meaning of the lower word or not?" for the upper row would be "No" and for the bottom row would be "Yes".