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Utilizing slope method as an alternative data analysis for functional near-infrared spectroscopy-derived cerebral hemodynamic responses

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ABSTRACT

The purpose was to propose an alternative data analysis for functional near-infrared spectroscopy (fNIRS)-derived hemodynamics as a function of cortical activation changes. We evaluated hemodynamic responses from the prefrontal cortex region while 38 participants performed a cognitive task. The task consisted of an arithmetic calculation with three levels of complexity (i.e., easy, medium and difficult). These task-dependent hemodynamic responses were analyzed by the slope method (i.e. using a linear regression through the cognitive task) and were compared with the corresponding responses obtained with a traditional approach of the amplitude method. Subjective scales of task loading (assessed by DP15 and NASA-TLX) and behavioral outcomes (performance and reaction time) were also recorded in response to the task complexity. Results revealed that the proposed slope method allowed a better discrimination in terms of cortical activation among all levels of mental workload. There was no significant increase in cortical activation between the medium and difficult levels ($p = .30$; $d = 0.09$) with the amplitude method while the slope coefficient was sensitive to the different levels ($p < .01$; $d = 0.32$). These preliminary results from a large sample size demonstrated that the slope method appears suitable for discriminating the changes in cortical activation with respect to the mental workload.

Relevance to industry: In this work, we proposed an optimum way of quantifying the mental workload of participants in terms of fNIRS-derived cerebral hemodynamic responses.

1. Introduction

A wide variety of daily tasks at work influence operators' mental load to meet task demands (Ryu and Myung, 2005; Ayaz et al., 2012). For instance, aircraft pilots need to allocate cognitive resources during landing approach and actual landing tasks (Takeuchi, 2000). Human behavior in complex task involves high brain resources, especially from the prefrontal cortex (PFC) area (Perrey et al., 2010). PFC is particularly well-described as being involved in the sophisticated neural processing and executive cognitive operations in humans (Gruber et al., 2001). Terminology in mental workload research has its roots in cognitive and physiological theories. Workload is the result of reaction to demand; it is the proportion of the capacity that is allocated for task performance. This construct is generally interpreted by both temporal demand and cognitive costs over the brain state (Pickup et al., 2010). The first is based on measures of reaction time (RT) and the second is based on measures of performance accuracy when performing a task. In other part, multidimensional subjective measurement techniques are valuable to assess mental workload (e.g., NASA-TLX). Finally, the mental load can be directly quantified by various psychophysiological measures (e.g., cardiac and respiratory activity, ocular blinking, skin sweating, etc.) or by the level of brain activity required for performing a given task (Fairclough et al., 2005; Ryu and Myung, 2005; Perrey et al., 2010). Hence, the level of brain activation might be related to a proportional mental workload associated to the level of the task difficulty.

Currently, the main neuroimaging techniques measure electrophysiological or hemodynamic signals over the scalp (e.g.,

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Abbreviations: ANOVA, analyses of variance; DP15, perceived difficulty of the task; EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy; NASA-TLX, nasa task load index; PFC, prefrontal cortex; RT, reaction time; STAI, State-trait anxiety inventory.

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electroencephalography, (EEG) or functional near-infrared spectroscopy, (fNIRS), respectively). Di Nocera et al. (2007) stipulated “it is well known that some EEG bandwidths and components of the event-related potentials are sensitive to variations in mental workload. However, these indices are difficult to collect and analyze in real time, and their reliability and stability are seldom assessed. Moreover, real-time filtering to obtain single-trial data is still an issue that is far from being solved.” Recently, some studies showed that the mental workload-related PFC activity can be alternatively assessed with fNIRS (Ayaz et al., 2012; Hirshfield et al., 2009; Izzetoglu et al., 2004, 2007; Perrey et al., 2010). fNIRS is a well-established noninvasive optical technique for estimating cortical activation and has the advantage to be weakly insensitive to motion artifact (Perrey, 2008). Thus, fNIRS appears suitable for detecting hemodynamic changes in real time while the subject is performing a functional task (e.g., sensory stimulation, cognitive task or physical exercise, León-Carrión and León-Domínguez, 2012; Perrey et al., 2010). A cortical activation from fNIRS signals is usually characterized by a large increase in oxyhemoglobin (oxy-Hb) with a lower delayed drop in deoxyhemoglobin (deoxy-Hb) (Ferrari and Quaresima, 2012; Gervain et al., 2011; Perrey, 2008, Perrey et al., 2010). In reality, the activation pattern of the fNIRS response turns out to be more variable and complex (Sato et al., 2005).

For example, Bauernfeind et al. (2008) observed inverse fNIRS response characterized by an increase of deoxy-Hb and a decrease of oxy-Hb over the left PFC with different mental arithmetic tasks (one subtraction and repetitive subtractions). Yang et al. (2009) did not find any difference between the fNIRS response of the bilateral PFC as function of two subtraction tasks with distinct difficulty levels. Using low, medium and high level of mental calculation tasks, Tsunashima et al. (2012) noticed that fNIRS changes over the bilateral PFC became larger as the task difficulty increased. These discrepancies may be explained by the differences in fNIRS signal processing. Prior to demonstrating such statistical comparisons between the tasks, Tsunashima et al. (2012) post-transformed the fNIRS signals (decomposition and reconstruction) using the discrete wavelet-based multi-resolution process. Then, in order to be used statistically they proposed the Z-scored signal for converting fNIRS data into a level of workload. For details about the effectiveness of this approach and analysis see Tsunashima et al. (2012). One drawback of this study was that the authors did not compare their processing method with a more traditional fNIRS analysis to judge its sensitivity.

Usually, the magnitude of the cortical activation level relies on the significance of data changes (i.e., pre-stimulation vs. stimulation) (Gervain et al., 2011). Commonly, the main variables of interest calculated to depict the fNIRS activation pattern are: difference of oxy-Hb and deoxy-Hb signal changes (Izzetoglu et al., 2004); sum of oxy-Hb and deoxy-Hb signal changes (Izzetoglu et al., 2004; Gervain et al., 2011); area under the curve (Limongi et al., 2009; Gagnon et al., 2012); Z-score (Tsunashima et al., 2012); amplitude response for oxy-Hb and deoxy-Hb (Perrey, 2008; Holper et al., 2009; Gervain et al., 2011) by comparing a baseline period to (i) the largest response obtained during a suitable temporal window during the stimulation period (Colier et al., 1999; Gervain et al., 2011) or (ii) the mean activation values measured throughout task (Tanida et al., 2004, 2007, 2008). However, the field of fNIRS still suffers from the lack of a commonly accepted standard by which investigators could describe and compare activation magnitudes. In fact, there is no real consensus in the literature on how to analyze the fNIRS data and construe for appropriate statistics. The sensitivity of the fNIRS experiment, judged on the basis of its ability to detect subtle activations is a function of not only the magnitude of the signal change, but also the dynamical fluctuation in the background signal. For the purpose of cognitive state assessment, the rate of change in blood oxygenation of fNIRS signals was shown to be sensitive to task load changes (Izzetoglu et al., 2004; Perrey et al., 2010; Tsunashima et al., 2012). Accordingly, a linear regression slope could be more powerful and simple for assessing the rate of change in the fNIRS signals in response to cognitive tasks. The quantification of the linear regression slope over the time course of the stimulation period offers advantages in computational speed and adaptability to real-time applications. This can be an alternative method for discriminating the typical brain oxygenation responses. Normally, the cortical activation pattern is expected to depict a positive slope for oxy-Hb accompanied by a lesser negative slope for deoxy-Hb.

The purpose of this study was to propose an alternative data analysis for fNIRS-derived hemodynamics as a function of cortical activation changes. We hypothesized that the slope method as compared to a more traditional method (amplitude response) is suitable and sensitive enough for discriminating the changes in cortical activation with respect to the mental workload during cognitive tasks.

2. Materials and methods

2.1. Participants

Thirty-eight healthy, female ($n = 13$) and male ($n = 25$) volunteer adults took part in the present study (age 29.8 ± 8.7 years; height 1.73 ± 0.1 m; weight 68.1 ± 12.6 kg). We recruited people with different levels of academic achievement and various professional occupations. The participant’s history and physical examination were negative for known injuries, neurological, endocrinological, respiratory and cardiovascular diseases or medication, which might affect brain function or perfusion. Each subject provided written informed consent prior to enrolling in this study. All procedures were approved by the local Ethics Committee (CPP ANSM Sud Méditérannée III, number 2010-11-05, Montpellier, France) conforming to the Declaration of Helsinki for human experimentation.

2.2. Experimental design and procedures

The experiment was conducted in a quiet room with no natural lighting (i.e., no window). A fluorescent tube provided the only illumination. The subjects were first seated in a very comfortable lounge chair with a headrest. This setup was followed by an explanation of the protocol before equipping them with optical NIRS sensors. Then, a session of familiarization for cognitive stimulation was proposed to the subjects with their eyes closed while staying as focused as possible. We employed a classical arithmetic task to stimulate cortical activation (Limongi et al., 2009; Sakatani et al., 2010; Tanida et al., 2004, 2007, 2008). The participants were asked to perform mathematical subtraction mentally as quickly as possible in within 60 s. For the testing session, the randomized experimental design was divided into three main levels of task difficulty (i.e., easy, medium and difficult) with three trials for each level. The timelines and running order of the testing session (blocks design) are shown in Fig. 1. We decided to use this type of experimental design to avoid ordering effects. The easy level consisted of subtracting numbers (comprised from 1 to 9) to a four-digit number sequentially (e.g., $3787-7 = ? - 4 = ? - 9 =$ etc.). Following each answer given by the subject, the investigator repeated the new four-digit number. The medium level consisted of subtracting serially a two-digit number (comprised only from 10 to 20) from a four-digit number (e.g., $3787-17 = ? - 14 = ? - 19 =$ etc.) (Limongi et al., 2009; Sakatani et al., 2010; Tanida et al., 2004, 2007, 2008). For the difficult level, the calculation consisted of subtracting a number between 20 and 100 (e.g., 3787−