Hemodynamic Response Asymmetry of the Prefrontal Cortex During a Cognitive Load Task

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***Abstract*—Investigations of the prefrontal cortex (PFC) asymmetry have been conducted in neuroscience research during cognitive load using electroencephalography (EEG) and other neuroimaging techniques. A few studies used functional near-infrared signals (fNIRS) to analyze asymmetry during cognitive load. This study examined the hemodynamic response asymmetry in the PFC area during N-back load memory tasks, including ive, 2-, and 3-back electroencephalography (EEG) and other neuroimaging techniques. A few studies used functional near-infrared signals (fNIRS) to analyze asymmetry during cognitive load. This study examined the hemodynamic response asymmetry in the PFC area during N-back load memory tasks, including 1-, 2-, and 3-back. The investigation results show that the asymmetry index value fluctuates as the level of memory load rises. In particular, the 1-back task's positive asymmetry index value** ($M = 0.2761, SD = 0.4139$) **suggested that left-hemisphere activity was more remarkable than right-hemisphere activation. The asymmetry index, on the other hand, revealed a negative value of** ($M = -0.2105, SD = 0.4252$) **and** ($M = -0.3665, SD = 1.2472$) **for the 2-back and 3-back memory tasks, respectively, indicating that the right hemisphere experienced a more significant increase in Hbo activation than the left.**

***Keywords*—fNIRS, Hemodynamic response, Prefrontal Cortex, Cognitive load, Asymmetry**

I. Introduction

Working memory (WM) is the temporary preservation of information recently encountered or recovered from long-term memory. These active representations are fleeting but can be maintained for longer periods through active rehearsal strategies. They can be confronted with various operations that manipulate information to make it helpful for goal-directed behavior. [1]. The ability to keep and manipulate information for brief periods is necessary for various cognitive activities, including working memory (WM). [2]. The significance of WM is illustrated by the presence of WM impairments in several cognition-related disorders, including attention-deficit hyperactivity disorder, Parkinson's disease, and schizophrenia. [3].

In order to aid diagnosis and improve treatment choices, many studies have investigated the biomarkers of various disorders during the past few decades. Cognitive neuroscientists attempt to separate the various components of working memory from localizing and clearly characterize their neural execution. WM is assumed to have its most significant base in the prefrontal cortex (PFC). According to previous research, patients experienced a major depressive disorder (MDD) have lower prefrontal oxygenation levels when performing cognitive activities, including verbal fluency [4], [5] and WM tasks [6], [7]. The anatomical and functional asymmetries of the brain's hemispheres are widely known. Although the physiological and genetic reasons for this asymmetry are unknown [8], [9], several convergent findings from in vivo and post-mortem studies in neuroanatomy, neurochemistry, neuropsychology, neuroimaging, and behavioral science strongly support its existence.

Furthermore, there is evidence that conditions such as brain injury and aging, which alter the anatomical and functional integrity of the brain, influence these asymmetries. Most of the previous research on prefrontal asymmetry and brain-computer interface (BCI) relied on EEG signals [10]–[12]. However, fNIRS shows more robustness to motion artifacts and environmental noise than EEG and functional magnetic resonance imaging (fMRI), making it a widely attractive technique for studying neural activity for outdoor experimentation [13]–[15]. This study investigates the hemodynamic asymmetry in the PFC during the N-back memory task. The purpose of the task for the participants is to contrast the current stimulus with one provided N item (N could be 1, 2, 3, or more) earlier during a continuous presentation. It is hypothesized that the oxygenated hemoglobin (Hbo) concentration change would increase with the level of cognitive load and decrease with a lesser cognitive load. However, examining how the PFC asymmetry varies on both hemispheres during the N-back working memory load is important.

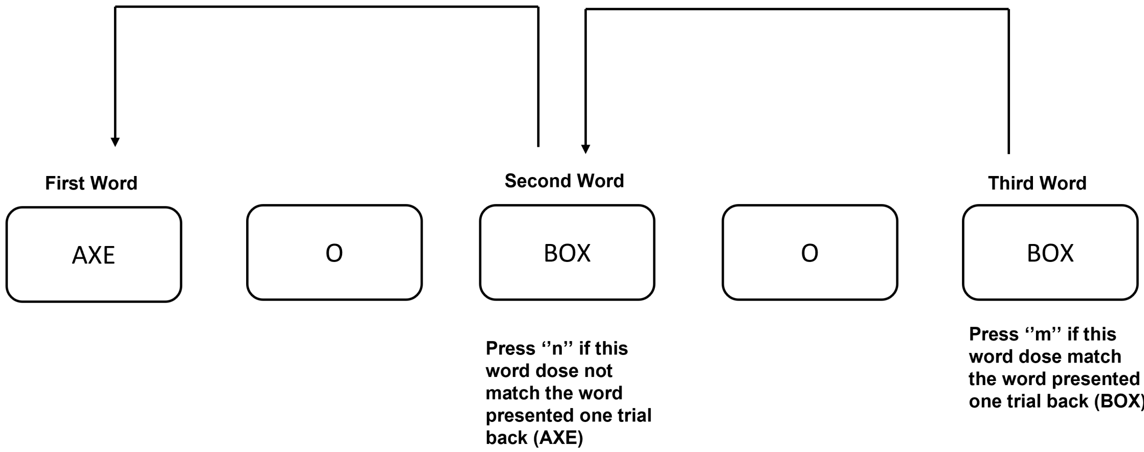

Fig. 1. 1-Back Memory task example .

II. METHOD

This section introduces the acquisition and analysis methods of the fNIRS data used in this study. Next, the processing of the hemodynamic response during the cognitive task is illustrated, and finally, the evaluation of the PFC asymmetry is described.

A. Data set Description

The hemodynamic response was recorded from seventy participants' parietal and prefrontal cortex during the N-back task with three N- back levels (N = 1,2,3). The example of the N-back protocol is illustrated in Fig 1. The data was acquired using a continuous-wave NIRSport2 device (NIRx Medical Technologies, LLC). The emitted light wavelengths of this system were 760 and 850 nm. NIRx acquisition software, Aurora fNIRS, was used to collect the signal at a 4.5 Hz sampling frequency. A total of 16 emitters and 16 detectors, forming 43 channels, covered the prefrontal and parietal cortex of the participant's brain. This paper considered only 20 subjects and three back-memory conditions. For more information about the data collection and experimental procedure, the reader is advised to refer to Meidenbauer et al. [16].

B. fNIRS Data Analysis

NIRS Brain AnalyzIR Toolbox based on MATLAB was implemented for the pre-processing and analyzing of the acquired fNIRS signals [17]. The imported raw data were transformed to optical density, and the modified Beer-Lambert Law was employed to evaluate the relative concentrations of oxygenated and deoxygenated hemoglobin [18]. After that, the optical data were converted to a voltage difference in the form of Hbo and Hbr, and first-level (subject-level) statistics were computed. Many potential factors, such as changes in heart rate, blood pressure, and respiration, can cause systemic hemodynamic changes in the measured fNIRS signals. [19]. These effects can be reduced using signal processing techniques such as the general linear model (GLM) with systemic regression and depth-resolved techniques described in [20]. In this work, a pre-whitening method (AR-IRLS) was employed [21]. The GLM coefficients for the N-back levels for each subject were calculated using a mixed-effects model with a fixed intercept for each experimental condition and a random intercept for the participants. Finally, the hemodynamic response function (HRF), including oxygenated (Hbo) and deoxygenated (Hbr) hemoglobin, was extracted for further analysis and statistical analysis.

C. Asymmetry Analysis

The difference in Hb concentration variations between the left and right dorsal PFC divided by the sum of those changes was used to quantify prefrontal asymmetry [22] as shown in Equation1:

$$AsymmetryIndex = (Hbo_L – Hbo_R)/(Hbo_L + Hbo_R) \quad (1)$$

A positive value reveals more activation of Hbo in the left dorsal prefrontal cortex (LDPFC), while a negative value indicates more Hbo activation in the right dorsal prefrontal cortex (RDPFC).

III. RESULTS

A. Hemodynamic Activation

Fig 2 illustrates the activation level of the Hbo and Hbr in the LDPFC and right RDPFC during the N-back memory task. The Hbo activation level in the LDPFC is higher than the activation level on the RDPFC side during the 1-back memory task. However, this activation did not change more during the 2-back memory task, while the Hbo activation levels of the RDPFC were increased during the 2-back and 3-back memory tasks. Hbr, on the other hand, did not change significantly across all back memory tasks. Thus, only Hbo measures were employed for further analysis.

The comparison between the Hbo activation level of the fNIRS channels in the dorsal part of the left and right PFC showed a varying level during the 1-back and 2-back memory tasks, as depicted in Fig 3. Particularly, during the 1-back

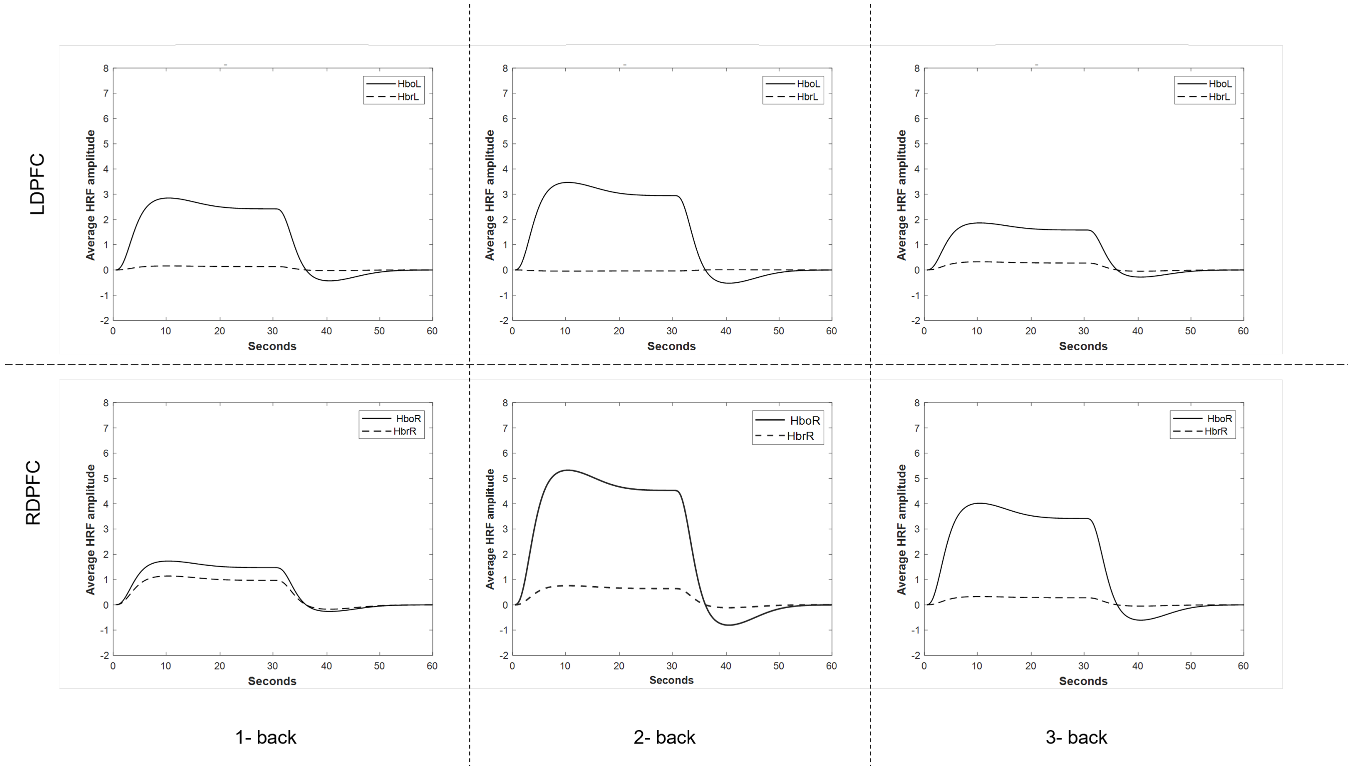

Fig. 2. Time course of Hbo vs Hbr in left and right prefrontal cortex during 1-back, 2-back and 3-back memory task.

condition, Hbo in the LDPFC exhibits a higher activation level $(M = 1.1894, SD = 0.0802)$ than those of the RDPFC $(M = 0.6752, SD = 0.0455)$ and this difference is significant $(F = 31.55, p < 0.0001)$. On the other hand, when the memory load increased during the 2-back task, the Hbo activation level in the RDPFC (M = 2.2018 , SD = 0.1485) was higher than that of the LDPFC $(M = 1.4368, SD = 0.0969)$ and this increment was also significant $(F = 18.610, p < 0.00001)$. For the 3-back task, the Hbo activation level in the RDPFC is higher $(M = 1.661, SD = 0.112)$ than the activation level of the LDPFC $(M = 0.770, SD = 0.0519)$ and this increment is also significant $(F = 52.05, p < 0.000001)$.

B. Asymmetry Analysis Results

One-way ANOVA was employed on the PFC asymmetry index obtained from the activation levels of the (LDPFC and RDPFC) during the N-back working memory load (1-back and 2- back) to evaluate how the working memory load generated an asymmetric PFC-Hbo. The results show that the asymmetry index for the 1-back task is (M = 0.2761, SD = 0.4139), the index for the 2-back task is (M = - 0.2105, SD = 0.4252), and the difference in asymmetry between the two N-back conditions is insignificant $(F = 0.8, p = 0.830)$. Additionally, the asymmetry index during the 3-back task is also negative $(M = -0.3665, SD = 1.2472)$ and it does not change significantly in comparison with 1- back task $(F = 1.53, p = 0.218\ )$ or 2-back task $(F = 0.29, p = 0.59)$.

IV. Discussion

In this work, the publicly available data set was used to investigate PFC asymmetry's hemodynamic response during the N-back memory test. We focused more on Hbo signals because they are more directly related to brain activity, and the N-back task has been shown to have a dominant effect [23]. The outcome of this analysis reveals the asymmetry index value's inconsistency with the memory load level increase. Particularly, during the 1-back task, the asymmetry index's value is positive, indicating that the activation in the left hemisphere is higher than in the right. On the other hand, with the increase of the memory load through the 2-back and 3-back memory tasks, the asymmetry index results in a negative value, indicating that the increase of the memory load leads to increased Hbo activation in the right hemisphere more than those in the left. These results align with related work, where the evidence for hemispheric asymmetry is conflicting. Some research [24], [25] reported substantially lower Hb in the left prefrontal areas during cognitive activities in depressed people, other studies did not observe such hemispheric differences [22], [26].

V. Conclusion

The hemodynamic responses in the prefrontal cortex were demonstrated to highlight the effect of cognitive load. The Hbo were selected for the analysis due to their impact on prefrontal activity during the N-back memory task. Then, the

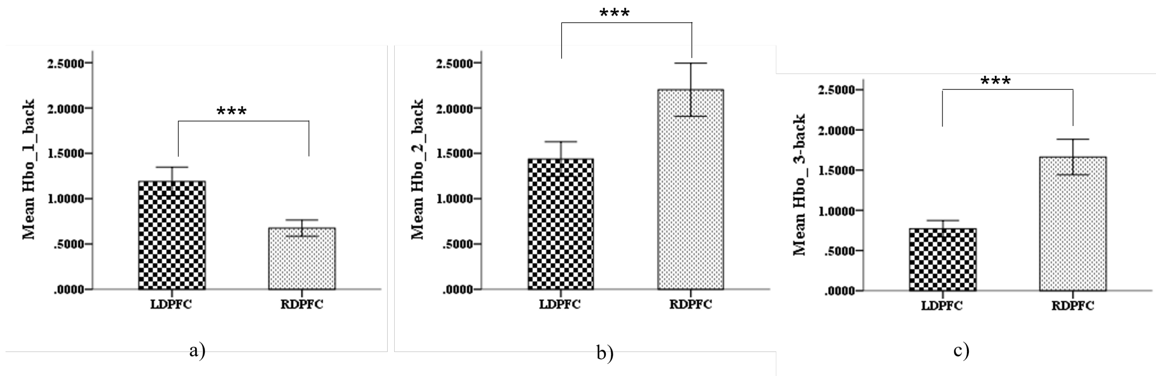

Fig. 3. Comperison results between left and right hemisphere during a) 1-back, b) 2-back and c) 3-back memory task. *** for $p < 0.0001$

Hbo asymmetry of the PFC was conducted during 1-back, 2-back, and 3-back memory load tasks. The results showed that the activation level on the left hemisphere was higher than on the right during a 1-back task, leading to a positive HBo asymmetry index. In the 2- and 3-back memory tasks, the Hbo asymmetry index was negative, indicating a higher activation level of the Hbo in the right hemisphere. Thus, the relation between the memory load level and the asymmetry index is inconsistent and requires more investigation with different memory load tasks.

ACKNOWLEDGMENT

This work received funding from the YUTP-FRG through PRF under grant number 015LC0-354.

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