Prefrontal Cortical Activation during Arithmetic Processing Differentiated by Cultures: A Preliminary fNIRS Study

Juanghong Yu, Yaozhang Pan, Kai Keng Ang, Cuntai Guan, and Darren J. Leamy

Abstract— **Understanding the neural basis of arithmetic processes could play an important role in improving mathematical education. This study investigates the prefrontal cortical activation among subjects from different cultural backgrounds while performing two difficulty levels of mental arithmetic tasks. The prefrontal cortical activation is measured using a high density 206 channels fNIRS. 8 healthy subjects, consisting of 5 Asians and 3 Europeans, are included in this study. NIRS-SPM is used to compute hemoglobin response changes and generate brain activation map based on two contrasts defined as Easy versus Rest and Hard versus Rest. Differences between the Asian group and the European group are found in both contrasts of Easy versus Rest and Hard versus Rest. The results suggest people with different cultural backgrounds engage different neural pathways during arithmetic processing.**

I. INTRODUCTION

One remarkable capability of the human brain is the encoding and manipulating on the information of quantities. Understanding how the brain deals with quantity and numbers is an important research that is relevant to the understanding of the development of mathematical ability. A good understanding of the development of mathematical ability can help to improve the education of mathematics. Studies in neuroscience had shown that the classical number-processing model involved verbal, analogue, and visual components [1], [2], [3]. The numbers involved in mental calculation had also been associated with language processing in many studies [1], [2], [4], [5], [6]. Studies had implicated that culture constraints on the brain in the process of reading [7], [8]. Since the mental calculation had been associated with language processing [1], [2], [4], [5], this motivated the investigation of arithmetic processing in people from different cultural backgrounds in this study.

An fMRI study in [9] had shown different activations between native English speaking group (NES) and native Chinese speaking group (NCS) in the premotor association area (PMA), perisylvian area and frontal cortex during arithmetic processing. The study claimed that people of different cultural backgrounds might engage different neural pathways in arithmetic processing. In addition, the differences might not be merely due to different languages but also due to specific mathematic processes.

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The prefrontal cortex is known to be a key part of the nervous system in controlling the action of maintaining the temporary storage of information known as working memory [10], [11], [12], [13], [14]. The investigation on the activity of prefrontal cortex may give us some hints on whether the working memory is engaged differently during the arithmetic processing. In this study, we measured the activity differences in the prefrontal cortex using fNIRS recording in people from two different cultural backgrounds: Asian and European, during arithmetic processing of two difficulty levels.

fNIRS as a non-invasive optical functional brain imaging technique measures concentration changes of oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) in the cerebral vessels by means of distinct absorption spectra in the near-infrared range [15]. fNIRS has been used in the study of hemodynamic changes during mental arithmetic task recently in some studies. In [16], a decrease in HbO and an increase in HbR concentrations measured over the prefrontal cortex were observed using a one-channel fNIRS druing different mental arithmetic tasks. In contrast, a study in [17] revealed that mental arithmetic task caused increase of HbO associated with decrease of HbR in the bilateral prefrontal cortices. In [18], the authors found higher increases of HbO in parietal brain regions of both hemispheres for the calculation compared to the reading-only condition. But the amount of activation seemed to depend on task modalities such as difficulty or complexity. The more recent study in [19] showed an increase of HbO in the dorsolateral prefrontal cortex (DLPFC) in parallel with a decrease in the medial area of the anterior prefrontal cortex (APFC) during simple mental arithmetic using a 52-channel fNIRS system. In [20], a fNIRS-based brain computer interface was proposed demonstrating the potential for recognizing the problem size effect in mental arithmetic task using a sophisticated feature extraction method based on the changes of HbO and HbR.

Our study focuses on the prefrontal cortical activations in people from different cultural backgrounds using a high density 206 fNIRS channels with two difficulty levels of mental arithmetic tasks. The experiment is undertaken on 8 healthy subjects, consisting of 5 Asians and 3 Europeans. NIRS-SPM software [21] is used to compute hemoglobin response changes and generate the contrast of brain activation map. The activation maps are generated based on two contrasts defined as Easy vs Rest and Hard vs Rest. Differences between the Asian group and the European group are found in both contrasts of Easy vs Rest and Hard vs Rest. The results implicate that besides the language related brain

areas, people of different cultural backgrounds would engage different neural pathways of working memory in arithmetic processing. More fundamental study should be undertaken to fully understand the mechanism behind our observations. To the best of our knowledge, there is no result of fNIRS-based arithmetical task study focusing on cultural difference in previous literatures.

II. METHOD

A. fNIRS data acquisition

The study was conducted on 8 healthy subjects (3 females, mean age 28.6±8.38) using a continuous wave fNIRS instrument NIRx DYnamic Near-Infrared Optical Tomography (NIRx DYNOT) Imaging System (NIRx Medical Technologies, LLC.), as shown in Fig. 1. Among the subjects, 5 came from Asian countries while the other 3 came from European countries. All subjects were fully informed about the experiment, and signed the consent form. The subjects' statistics are shown in Table I.

Fig. 1. Subject during arithmetic tasks and the device used for the fNIRS signal recording

TABLE I
THE STATISTICS OF SUBJECTS

Subject	Age	Gender	Nationality	Culture	Handedness
1	22	Male	Malaysian	Asian	Right
2	45	Female	Singaporean	Asian	Right
3	22	Female	German	European	Right
4	28	Male	Chinese	Asian	Right
5	25	Male	Irish	European	Right
6	24	Male	German	European	Right
7	25	Female	Indian	Asian	Right
8	38	Male	Singaporean	Asian	Right

We measured oxygenated and deoxygenated hemoglobin changes of cortical with two wavelengths (λ = 760 & 830 nm) and sampling rate of 1.81 Hz. 32 co-located optodes, each serving as source and detector, were put on the forehead of the subject's head as shown in Fig. 2. The optodes were fixed over the prefrontal area using an open scaffolding

Fig. 2. Positions of optodes arrays

structure with individually spring-loaded fibers to ensure stable optical contact.

For each wavelength, 32 channels of signal were measured from 32 detectors for each source, which yielded a total of 1024 channels. As the trajectory of the photon path from source to detector was assumed to be a "banana" shape between two optobes[22], the signal quality of a source-detector pair was considered to be good enough only when the path length was within an effective range. We used only those channels with source-detector distances between 1.5 to 3.5 cm measured using the Xensor digitizer. As result, a total of 206 channels were used for each wavelength.

B. Experimental Protocol

HbO and HbR changes were measured when subjects were performing arithmetic tasks with two difficulty levels. The subjects sat in a comfortable chair in a room with normal lighting, facing a computer screen on which task cues and mathematic questions were visually presented. A keyboard was put nearby for them to answer the questions. They were asked to relax before the data collection and during resting state. They were also asked to minimize movement and to respond as quick and as correct as possible.

NRIS signal has inherent latency of the hemodynamic response. The peak response occurs approximately 5-8 s post-stimulus [23]. With consideration of the latency effect, we designed self-paced variable action period of 0 - 36s followed by a 20s rest period to make sure the signal of performing arithmetic task contains the peak values of hemodynamic changes. The experimental paradigm is shown in Fig. 3.

The subjects performed a total of 40 trials of arithmetic tasks which were evenly distributed into 2 difficulty levels of easy and hard. Each trial has a set of 3 numerical arithmetic
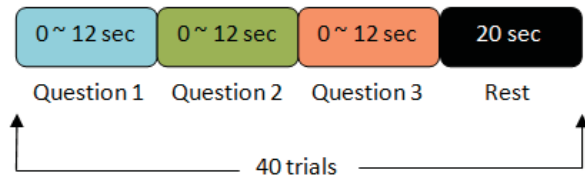
Fig. 3. Experimental paradigm: the block is repeated for easy and hard arithmetic task respectively

A high pass filter based on a discrete cosine transform (DCT) with a cutoff frequency of 80 Hz [25] and low pass filter hrf were used. The brain activation maps were generated based on two contrasts: Easy vs Rest and Hard vs Rest for two different cultural groups, with $p < 0.05$. Fig. 5 demonstrated the spatial registration of fNIRS channels over prefrontal area in NIRS-SPM.
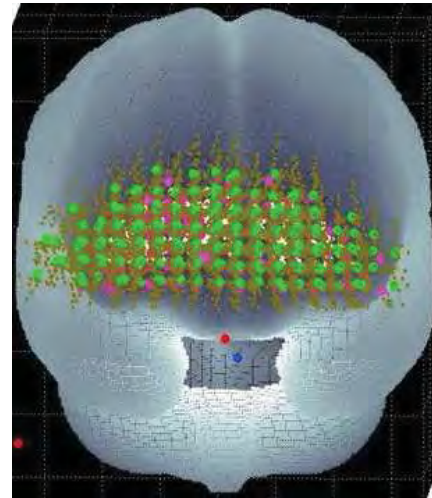
questions from the same difficulty level. All questions are presented in the form of arabic numerals. The subjects were asked to perform additions of 3-digits number with 2-digits number without carryover for the easy tasks (eg. 456 + 12), and additions of 4-digits numbers with 3-digits with at least 1 carry over (eg. 4567 + 821) for the hard tasks. At the start of each trial, a question was displayed for a maximum of 12 s. The next question will be displayed immediately if the subject responded within 12 s, or at the end of 12 s. A period of 20 s of rest condition was given between each trial. If all the 3 questions from a trial were correctly answered, then the trial was considered correct.

C. fNIRS data processing

NIRS-SPM [21] was used to analyze the fNIRS data statistically. NIRS-SPM uses modified Beer-Lambert law [24] to compute the concentration changes of HbO and HbR from optical density changes and provides activation maps of HbO, HbR with super-resolution activation localization based on general linear model and Sun's tube formula [21].

Fig. 5. Spatial registration of fNIRS channels over prefrontal area in NIRS-SPM

III. RESULTS

Fig. 4 shows the prefrontal cortical activations during two arithmetic tasks: easy and hard, in two different subject groups: Asian and European. The upper row shows the
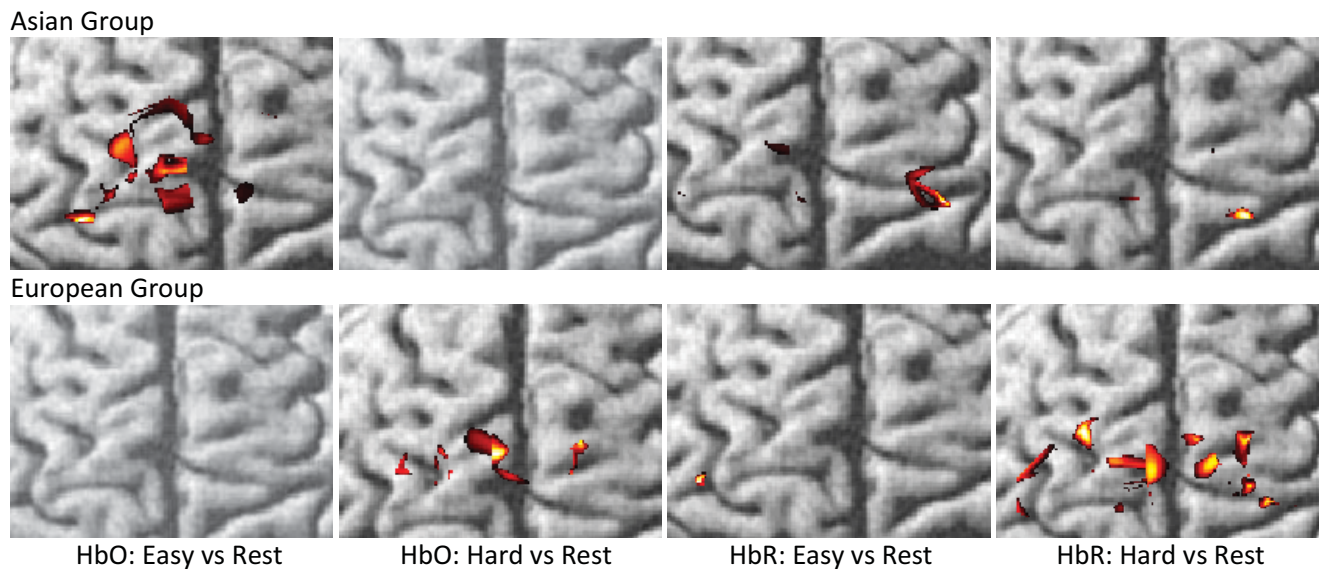

Fig. 4. Different prefrontal activations in the Asian group and the European group during arithmetic processing: the upper row is activations of the Asian group analysis and the lower row is those of the European group analysis. Each row consists of the HbO activation (left two columns) and the HbR activation (right two columns) with contrasts of Easy vs Rest and Hard vs Rest, $p < 0.05$.

activations of the Asian group and the lower row shows the activation of the European group. Each row consists of HbO activation (left two columns) and HbR activation (right two columns) with contrasts of Easy versus Rest and Hard versus Rest. For a clearer illustration, only the prefrontal activation is shown since all the optodes are fixed over the prefrontal area as shown in Fig. 5.

Differences between the Asian group and the European group are found in both contrasts of Easy versus Rest and Hard versus Rest. The results shows that the easy arithmetic task induces obvious changes of brain activity in prefrontal cortex in the Asian group while no significant changes are seen in the European group. In contrast, the hard arithmetic task induces more extensive changes of prefrontal cortical activity in the European group compared to the Asian group. This implies two different trends between the Asian and the European group as the arithmetic difficulty level increased: a trend of increase in prefrontal area in the European group, while a trend of decrease in prefrontal area in the Asian group.

IV. Discussion

The two different trends between the Asian and the European group as the arithmetic difficulty level increased may imply that the prefrontal cortex activations engage differently during arithmetic processing in people with different cultural backgrounds. However, where the differences of prefrontal cortical activations during arithmetic processing in people with different cultural backgrounds comes from are worth investigating to better understand the fundamental mechanism of the arithmetic processing of human brain. We will further investigate these problems by designing more comprehensive experiments, for example, to utilize fNIRs optodes covering full head and let the subjects solve more types of arithmetical problem, etc.

V. Conclusions

In this work, prefrontal activations related to arithmetic processing of two difficulty levels were delineated by fNIRS. Differences in the activation map between the Asian group and the European group were observed. These differences indicated that the prefrontal cortex activations might engage differently during arithmetic processing in people with different cultural backgrounds. Future work would exploit the differences in fNIRS using optodes covering full head, with larger group size and various types of arithmetic problem. The fundamental mechanism of these differences is also worth investigating.

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