Quantification of Mental Stress using fNIRS Signals

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***Abstract*— In this study, we propose functional near infrared spectroscopy (fNIRS) to objectively grade different levels of mental stress. The levels of stress were set based on arithmetic task difficulty, time pressure and negative feedback about peer performance. We examined the proposed approach on twelve human subjects using the Montreal Imaging Stress Task. The experiment results revealed a reduction in cortical activations at prefrontal cortex when stressed, and the differences in hemodynamic response between control condition and under stress were significant with mean *p-values* of 0.0023, 0.00015 and 0.0004 for arithmetic difficulty level one, two and three, respectively. We thus confirm the feasibility of fNIRS in grading mental stress.**

Keywords—Stress, fNIRS, neuroimaging

I. Introduction

Conventionally, questionnaires are used as a tool to assess mental stress. However, such method is subjective [1]. Stress has been reported to activate the hypothalamus-pituitary-adrenocortical axis (HPA axis) and sympathetic nervous system (SNS) causing an increase in cortisol secretion in the adrenal cortex. Therefore, the level of cortisol is widely accepted as a biomarker of stress [2].

Besides cortisol, stress can be detected from human bio-signals [3, 4]. Researchers have found a relationship between salivary cortisol levels and physiological variable changes such as heart rate variability (HRV), electrodermal response (EDR) and blood pressure (BP) [4, 5]. Stress causes a decrease in the high frequency components of heart beat interval and an increase in the low frequency components, respectively. Skin conductivity on the other hand varies with the changes in skin moisture level revealing the changes in SNS. It has been reported to increase during a stressful task and can be acquired using a galvanic skin response (GSR) sensor [6].

Changes in autonomous nervous system (ANS) can be represented by electroencephalography (EEG) signals [7]. EEG is one of the most studied non-invasive neuroimaging modality that measures the electric potential of cortical activation. EEG has the advantages of temporal resolution, ease of use, and low set-up cost. Its signal components are categorized by frequency bands; Delta (0.5-4 Hz), Theta (4-8 Hz), Alpha (8-13 Hz) and Beta (14-30 Hz). Each of the frequency band can be used as an indicator of one's mental state. However, EEG has some limitations as it has poor spatial resolution and its signals are susceptive to noise. To overcome these limitations, we proposed a new neuroimaging modality to objectively grade the levels of mental stress.

Functional Near-infrared Spectroscopy (fNIRS) is a non-invasive brain imaging technology based on hemodynamic responses to cortical activation [8]. It uses near-infrared light in the wavelength range 650-900 nm and estimates the changes in oxygenated and deoxygenated hemoglobin concentrations (O_2Hb and HHb) using modified Beer-Lambert law [9]. fNIRS has several advantages over other neuro-imaging modalities. Compared to EEG, it has better spatial resolution and less affected by noise [10]. Compared to functional magnetic resonance imaging (fMRI) and positron emission topography (PET), fNIRS is portable, cheaper and does not confine the subjects to lying position.

In this study, we aim to grade mental stress by measuring the hemodynamic response from the prefrontal cortex (PFC). PFC is the brain region responsible for regulating thoughts, actions and emotions. It is also the most sensitive area in the brain to detrimental effects of stress exposure [11]. According to previous fMRI studies [12, 13], solving arithmetic tasks under time pressure induces mental stress on the PFC. We developed three levels of arithmetic task difficulty to induce stress on the participants. Besides the arithmetic task difficulty, time pressure and negative feedback of peer performance were the main target in inducing stress in this study. To the best of our knowledge, this is the first study to quantify the levels of stress based on hemodynamic responses to cortical activations.

II. Methodology

A. Subjects

Twelve healthy, right-handed adults (aged 22 ± 4) participated in this study. All participants were informed prior to the experiment and gave written consent, in accordance with the Declaration of Helsinki and ethics approval granted by local ethics review committee at Universiti Teknologi PETRONAS. None of the participants had a history of psychiatric, neurological illness or psychotropic drug use. To avoid any environmental stress, all participants were seated in a comfortable chair in a room with good air condition.

B. Stress stimuli

The experiment was developed based on the Montreal Imaging Stress Task (MIST) [13]. In this study, the arithmetic task was defined at three levels of difficulty, where each level corresponded to one level of stress. The task at level one (L1) involved 3-one digit integer (ranging from 0 to 9) and used the operands of + or – (example 9+1-6). At level two (L2), the task involved 3 integers (ranging from 0 to 99) with at least 2 two-digit integers using the operands of +, –, and × (example 12×3-30). At level three (L3), the task involved 4 integer numbers (ranging from 0 to 99) and the operands include +, –, ×, / and ÷ (example 7-99/3+35). Besides the task difficulty, time pressure and negative feedback about peer performance were implemented to induce stress on the participants. Participants were first trained at each level of task difficulty and the average time for each individual in answering the questions was recorded. This recorded time was then reduced by 10% and used as time pressure on the participants. Moreover, feedback of answering the questions ("correct", "incorrect" or "timeout") and performance indicators (one for the participant's performance and one for the averaged peer performance fixed at 90% accuracy) were displayed on the computer monitor to further induce stress in participants.

C. *Experiment procedure*

At the beginning of the experiment, participants were instructed to avoid any head and body movements and deep breathing during fNIRS measurements. The experiment was performed in four successive sessions. In first session, a brief introduction was given to each participant to be familiar with the proposed tasks. In second session, the participants were trained for five minutes at each level of difficulty in the mental arithmetic (MA) task to estimate average time taken to answer each question. In third session (i.e. control session), the fNIRS cap was attached to the participant's head and fNIRS signals were recorded for a total duration of 15 minutes while solving arithmetic problems at three levels of difficulty without any time limit per question. After fNIRS recording, a questionnaire was filled by the participants as self-reporting about task loading according to NASA-TLX rating scale [14]. The fourth session (i.e. stress phase) was similarly as the control phase where the fNIRS was recorded for 15 minutes but under stress conditions (time limit and negative feedback). Similar questionnaire about task loading was again completed.

The entire recording duration for each participant is nearly 1 hour.

Fig. 1 gives an overview of the experiment protocol and the block design. Each block consisted of 40 seconds of mental arithmetic task and 30 seconds of rest. During the 40 seconds task, participants were shown mental arithmetic tasks on the computer screen and had to solve them as fast as they could (i.e. the control session) or within a given amount of time (i.e. the stress session). During the 30 s rest, participants needed to focus on a fixation cross with black background to sustain participants' attention to the monitor display.

D. *Functional near infrared spectroscopy*

Relative concentrations of oxygenated and deoxygenated hemoglobin were recorded with 16 optodes (8 sources and 8 detectors) of fNIRS system, OT-R40 (Hitachi Medical, Japan) using two infrared wavelengths (695nm and 830nm). The sampling frequency was set to 10 Hz. The distance between pairs of source and detector probes was set to 3.0 cm. Channel (Ch) was defined as the measurement area between a pair of source-detector optodes. A total of 27 channels were measured in this study and PFC was the region of interest. Fig. 2 shows the full configuration of measurement channels.

E. *fNIRS analysis*

The fNIRS signals were transformed to concentration changes of oxygenated, deoxygenated and total hemoglobin using modified Beer-Lambert law [9]. In order to reduce the noise and motion artifacts, fNIRS signals passed through several pre-processing steps using the plug-in-based analysis software Platform for Optical Topography Analysis Tool (developed by Hitachi, CRL; run on MATLAB). The process involved removing the motion artifacts [15], filtering the signal in the range of 0.012 to 0.8 Hz using a 5th order Butterworth filter, baseline correction, and moving average. In baseline correction, we defined a period from 5s prior to task condition to the end of each MA task as an analysis block. Linear regression by least mean square method was applied to remove any dc drift in fNIRS recordings [16] before we averaged all the blocks and performed statistical analysis on the changes of O_2Hb. The entire steps are similar as to our previous studies [17-23].

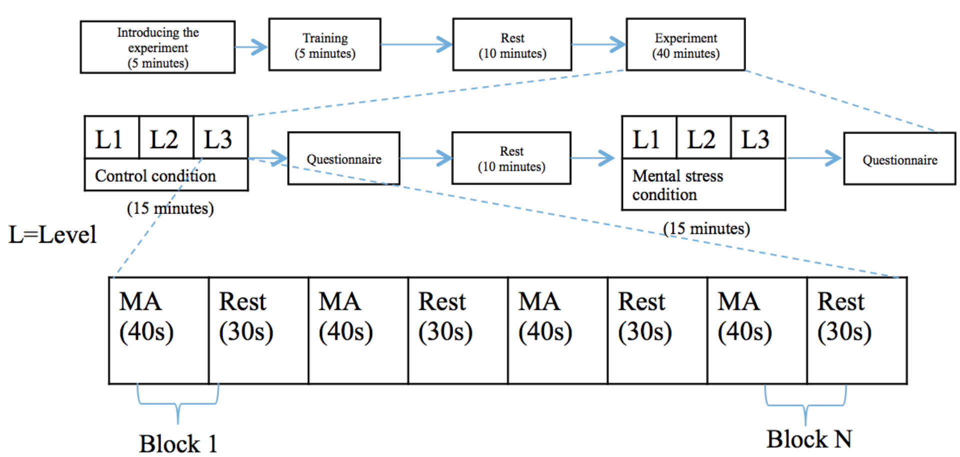

Figure 1. Experiment protocol of mental stress study. The labels L1, L2 and L3 represent the levels of mental arithmetic task and MA stands for mental arithmetic. Six recordings were performed in this experiment; three for control condition and three for stress condition. In each recording, there were four blocks. In each block, mental arithmetic was allocated for 40 s followed by 30 s rest.

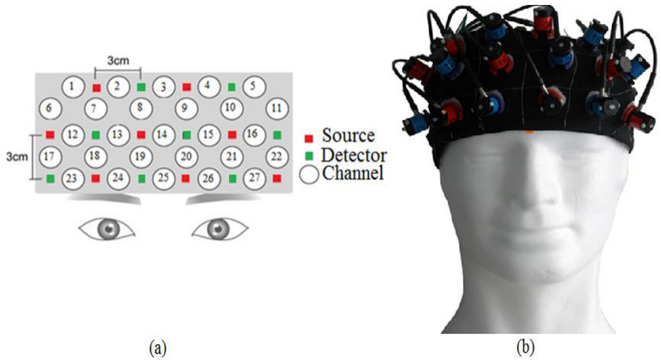

Figure 2. Measurement setup: (a) channel configuration and (b) probe holder worn on the PFC area. Eight sources and eight detectors used in the measurements corresponding to 27-channels over the PFC area.

III. RESULT AND DISCUSSION

The results obtained from level one (i.e. control phase) demonstrated significant increase in O_2Hb due to MA task, as compared to baseline. Under stress condition, however, there was a significant reduction in this change in O_2Hb. This revealed that stress might have impaired the PFC and resulted in reduced cortical activities. Fig. 3(a) and (b) illustrate the topographical map of O_2Hb under control and stress conditions, respectively. The channel numbers were marked on the topography maps to indicate their particular locations in the PFC area. Red colour indicates high concentration level and blue colour indicates less concentration level of O_2Hb.

Similar results were obtained at level two and level three of arithmetic task difficulty where a significant decline was observed in the concentration change of oxygenated hemoglobin under stress condition. Fig. 4 and Fig. 5 show the topographical maps of oxygenated hemoglobin concentrations in level two and level three under the two conditions, respectively. In addition, we studied, at each level of mental stress, the difference in hemodynamic response to MA task under the control and the stress conditions, and their correlation with mental stress level using two-sample t-test analysis. We found a significant decrease in oxygenated hemoglobin concentration from control condition to stress condition with mean *p-value* of 0.0023, 0.00015 and 0.0004 for level one, level two and level three, respectively.

We further examined the performance of each participant in answering the arithmetic questions (accuracy score), and how they were related to the hemodynamic response. Fig. 6 shows the relationship between the accuracy score by each participant (twelve participants in total) and the mean change in oxygenated hemoglobin concentration, at level 1 difficulty. We found a good agreement in their performance when their cortical activation was affected by stress (R^2 = 0.86963). When cross-checked with the results of self-reporting about task loading questionnaires, NASA-TLX rating scales showed no significant differences in the three mental stress levels. Admittedly the sample size is limited, the results suggested that subjective assessment using questionnaire might not be sensitive enough as a tool for quantifying mental stress levels.

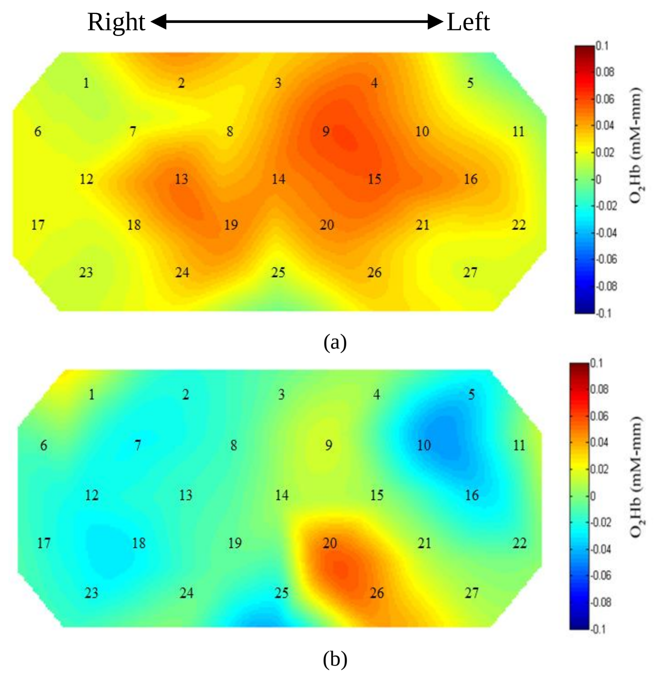

Figure 3. Topographical map of oxygenated hemoglobin, (a) under control condition and (b) under stress condition, at level 1 for average of 12 subjects. Red colour indicates high concentration levels of oxygenated hemoglobin and blue colour indicates less activation or distortion.

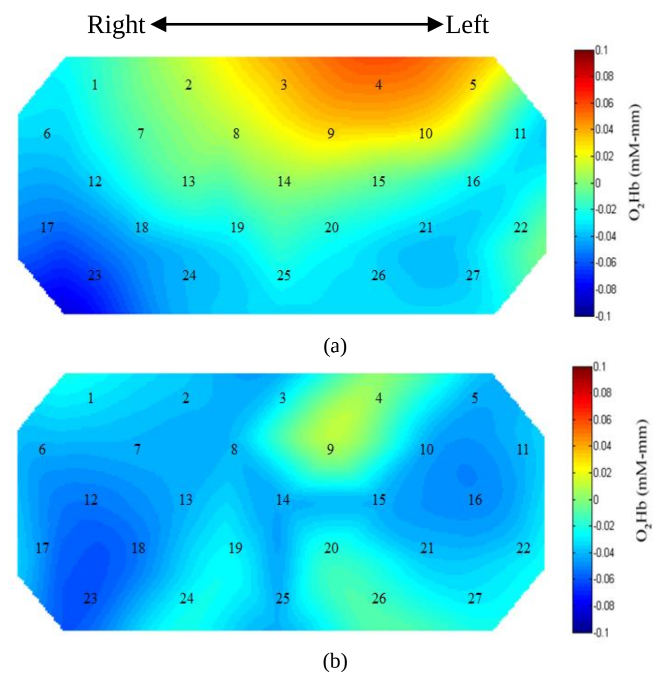

Figure 4. Topographical map of oxygenated hemoglobin, (a) under control condition and (b) under stress condition, at level 2 for average of 12 subjects. Red colour indicates high concentration levels of oxygenated hemoglobin and blue colour indicates less activation.

Furthermore, we found the hemodynamic response to mental stress were highly localized. Based on the repeated measurements (three measurements for each level of mental stress), we observed a high reduction on oxygenated haemoglobin concentration on the right PFC and dorsolateral PFC in all the three levels of mental stress. To confirm the right dominant of PFC to mental stress, we calculated the laterality index at the three levels of stress {i.e., [(right-left) / (right+left)]; LIS}. LIS <0 indicates less activity of the right PFC, while LIS >0 indicates less activity of the left PFC. The results of LIS demonstrated right dominant PFC with mean LIS value of -0.0821 and -0.1428 in level one and level two of mental stress respectively. In level three however, the result demonstrated that all PFC region were highly affected by stress. This indicate that right PFC and dorsolateral PFC are the most sensitive brain regions to the detrimental effects to stress exposure.

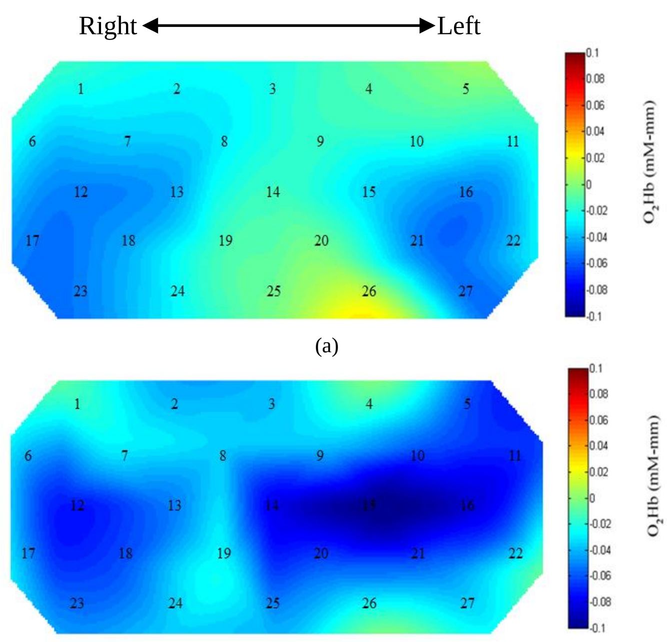

Figure 5. Topographical map of oxygenated hemoglobin, (a) under control condition and (b) under stress condition, at level 3 for average of 12 subjects. Red colour indicates high concentration levels of oxygenated hemoglobin and blue colour indicates less activation.

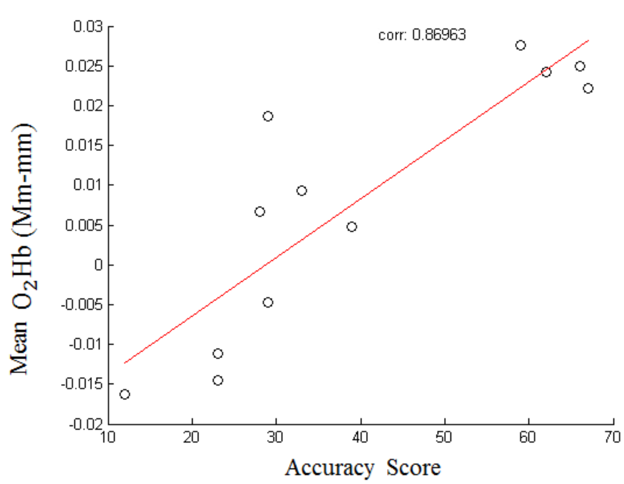

Figure 6. The oxygenated hemoglobin is positively correlated with performance and negatively correlated with stress level, (oxygenated hemoglobin decrease with increasing the level of stress). The figure demonstrates that less accuracy associated with high level of stress.

IV. Conclusion

In this study, we investigated with twelve human subjects if fNIRS signals could be used in grading mental stress. The experiment results showed that we could discriminate stress condition (with time pressure and negative feedback about peer performance) from control condition, based on hemodynamic response in the PFC measured with fNIRS, with mean *p-values* of *0.0023, 0.00015, and 0.0004* for arithmetic task difficulty level one, level two and level three, respectively. Using two sample t test, we found right PFC and dorsolateral PFC as the brain regions sensitive to mental stress. In contrast, the results from questionnaire approach (self-reporting about task load) indicated that the engagement of participants reduced with increasing level of task difficulty, but were not significant. In short, our study supported the suggestion of using fNIRS to objectively grade the levels of mental stress.

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