Prediction of Human Cognitive Abilities based on EEG Measurements

Yisi Liu, Wei Lun Lim, Xiyuan Hou, Olga Sourina
Fraunhofer IDM@NTU
Nanyang Technological University
Singapore
{liuys, wllim2, houxy, eosourina}@ntu.edu.sg

Lipo Wang
School of EEE
Nanyang Technological University
Singapore
elpwang@ntu.edu.sg

***Abstract*—The difference in cognitive abilities of humans could be assessed by indexes extracted from EEG. In this paper, we propose and implement an experiment with 60 subjects to study how cognitive abilities can be identified through EEG. We analyzed parameters of the individual frequency band that can be used for prediction of cognitive abilities of subjects. In the experiment, the subjects performed cognitive tests with EEG recording done prior to the tests. Different patterns of alpha band activity are proven to be indicators of cognitive abilities and performances. Our hypothesis is that cognitive abilities can be predicted based on EEG measurements. The results of analysis of the experiment show significant correlation between subjects' cognitive abilities assessed by the tests and the EEG measurements.**

Keywords-EEG; cognitive abilities; multitasking; individual alpha peak frequency; individual alpha bandwidth

I. INTRODUCTION

There are various applications when assessment of cognitive abilities of humans is needed to be completed, e.g. to analyze improvement of cognitive abilities if any after training intervention; to select candidates with higher cognitive abilities. Usually psychological tests are used and different parameters such as reaction time or response correctness in the tests are considered as the indicators of cognitive abilities. However, taking tests is time-consuming and could be up to hours.

Indexes extracted from EEG could be considered as a novel tool for cognitive abilities assessment. To get the parameters from EEG, a short length recording is needed. In this paper, we propose and implement an experiment with 60 subjects to study how cognitive abilities such as multitasking ability and stress tolerance can be assessed through EEG. All subjects took a cognitive test to evaluate their ability on multitasking with EEG recording performed before the tests. The individual alpha peak frequency is extracted from the recordings and the correlation between the individual alpha peak frequency and performance in the multitasking test is studied. Our hypothesis is that cognitive abilities such as multitasking ability and stress tolerance can be predicted based on EEG measurements. The resulting analysis of the experiment show significant correlation between subjects' cognitive abilities assessed by the test and the EEG measurements.

The paper is organized as follows. In Section II, the review on EEG-based psychosocial indexes is given. In Section III, the method, including recruited participants, Vienna SIMKAP test, and the calculation of individual alpha peak frequency are described. In Section IV, the analysis result is shown. Section V concludes the paper.

II. REVIEW ON EEG-BASED PSYCHOLOGICAL INDEXES

Various studies showed that indexes extracted from EEG can reflect the cognitive abilities of subjects.

In [1-6], individual alpha band is shown to be an indicator of cognitive abilities. For example, it is found that people who use more of their parietal lobe have a higher cognitive ability, while people who make greater use of their frontal lobe have a lower cognitive ability [1]. It is also shown that the intelligence level of healthy adults can be reflected by the individual alpha peak frequency and mean power of alpha band [2]. In [3], it is claimed that a decrease in the performance in a modified version of Schneider's test and Shiffrin's memory search paradigm is accompanied by a decrease in the individual alpha peak frequency. In [4], a study is done with children and the results show that children from the same age group but with higher individual alpha peak frequency have higher reading performance than the others. Additionally, [5, 6] shows that the individual alpha peak frequency is a positive indicator of cognitive abilities such as attention and the speed of information processing. Besides the above-mentioned parameters from individual alpha band, the relative theta power is also studied. In [7], it shows that the relative theta power has a significant positive correlation with the immediate and delayed verbal recall, and attention in healthy older adults.

The P300 or P3 component of the Event Related Potential (ERP) from the EEG is another parameter that is studied for relationship with human cognitive abilities. P300 amplitude has been found to be positively correlated with IQ [8]. It has also been shown that individual differences in cognitive abilities can be studied from the P300 amplitude and latency, for example, in a mental rotation task [9], attentional blink task [10] and navigation performance in a driving task [11].

From the review above, we can see that EEG parameters/indexes can be used as the indicators to assess cognitive abilities of people. Instead of taking various

978-1-4673-9403-1/15 $31.00 © 2015 IEEE
DOI 10.1109/CW.2015.47

psychological tests to assess different cognitive abilities, one session of EEG recording may be enough to get information about the subject's IQ, verbal, reasoning ability and so on. The reliability of EEG to assess the changes in cognitive functions is confirmed in [12]. As the alpha peak frequency is proven to be an indicator of intelligence level, performance in different tests [2-6], it is proposed to be used to assess the multitasking ability in our work.

III. METHOD

A. Participants

60 male students between 21 to 35 years of age participated in the experiment. All of them are students from Nanyang Technological University and none of them have any reported mental disorders.

B. Vienna Test System - SIMKAP Test

5 assessment sessions were carried out and the "Simultaneous Capacity/Multitasking" (SIMKAP) test of the Vienna test system was used in each session. The first session is considered as the pre-try session for the participants to become familiar with the test and eliminate learning effects, as subject performance can be sharply reduced due to unfamiliarity with the tests [13]. This session is excluded in the processing.

The Vienna Test System is a software tool developed by Schuhfried GmbH for the psychological assessment of individuals. In this paper, the SIMKAP module of the system is used. Two parameters including "Simultaneous Capacity" and "Stress Tolerance" are used to assess multitasking abilities. Simultaneous Capacity is defined as the performance achieved when working on routine tasks and tasks demanding cognitive performance (problem solving) concurrently, also termed "Multitasking". Stress Tolerance is defined as the degree to which performance differs when dealing with routine tasks under normal (baseline) conditions compared to a situation with stress (multitasking).

Simultaneous capacity can be used as a measure of concurrent multitasking ability while stress tolerance can be seen as a measure for mental workload capacity.

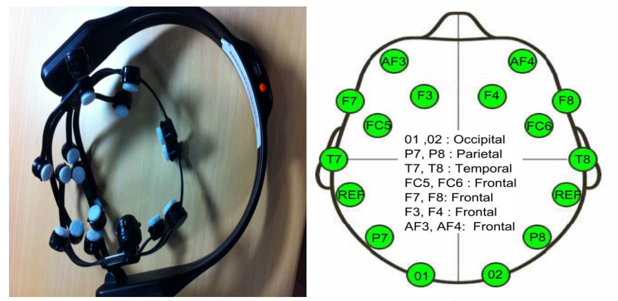
The test itself comprises of 5 sub-tests, the first 3 baseline tasks require the subject to cross out similar items on the right panel based on the items that are already crossed out on the left panel. This task has 3 variations, where the items are depicted as numbers, letters, and figures respectively. The final baseline test is a problem solving task which includes basic arithmetic questions, identification of similar object questions, and comparison questions that are all delivered orally to the subject via the computer headphones or speaker. The final test is the multitasking test which includes the 4 baseline tasks described above as well as an additional requirement of consulting a telephone book or calendar for an answer when prompted orally. Furthermore, some of the problem solving/telephone book/calendar tasks have an additional requirement of inputting the correct answer at a given time shown on the clock.

"Simultaneous Capacity" and "Stress Tolerance" are the main numerical result of the SIMKAP test and are the key variables that are used in this work.

C. EEG Data Recording

1 minute eyes-open and eyes-closed EEG were recorded right before each test to get the individual alpha peak frequency.

The Emotiv Headset as shown in Fig. 1 (a) was used to capture users' EEG signals wirelessly with an USB receiver. It has 14 channels locating at AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 as shown in Fig. 1 (b).



(a) (b)

Figure 1. (a) Emotiv headset. (b) Location of 14 electrodes.

D. Calculation of IAPF and IAW

The individual alpha peak frequency is the peak frequency of the eyes-closed EEG. As it is found that the EEG spectrum is suppressed when the eyes are opened compared to the eyes-closed condition, the individual alpha band width is calculated using both eyes-closed and eyes-open EEG data. It is defined as the suppressed frequency range when the power spectral density of eyes-open and eyes-closed EEG signals is compared [6, 14] as shown in Fig. 2. In Fig. 2, the red curve (upper curve) is the power spectral density plot of eyes-closed EEG, and the blue curve is the power spectral density plot of eyes-open EEG. The frequency where the maximum of the power spectral density is located in the eye-closed EEG curve is the alpha peak frequency. The intersection on the left side of these two curves is the lower alpha boundary, and the intersection on the right-hand side of these two curves is the upper alpha boundary.

The calculation of the individual alpha peak, lower and upper boundary of the alpha band is implemented in MATLAB. The programme pseudocode is given as follows.

1:**Input:** 1-minute eyes-closed and eye-open EEG recording
2:**Output:** Alpha peak, alpha band lower boundary, alpha band upper boundary.
3:RawData_EyesOpen←importData(Eyes-open EEG)
// Import the 1-minute eyes-open EEG recording from channel P8 (the location of P8 is illustrated in Fig. 1(b))
4:RawData_EyesClosed←importData(Eyes-closed EEG)
//Import the 1-minute eye-closed EEG recording from channel P8
5:PSD_EyesOpen←PowerSpectralDensity(RawData_EyesOpen)

//Calculate the power spectral density of the eyes-open EEG using Fourier Transform (the equations are listed below)
6:PSD_EyesClosed←PowerSpectralDensity(RawData_EyesClosed)
//Calculate the power spectral density (PSD) of the eyes-closed EEG using Fourier Transform (the equations are listed below)
7:AlphaPeakFrequency=SearchMax(PSD_EyesClosed)
//Find the max PSD and the corresponding frequency values from PSD of the eyes-closed EEG data, which is the alpha peak frequency based on the definition as shown in Fig. 2
8:SmoothPSD_EyesOpen←smooth(PSD_EyesOpen)
//Smooth the PSD with loess method for better plotting and alpha band boundary searching
9:SmoothPSD_EyesClosed←smooth(PSD_EyesClosed)
//Smooth the PSD with loess method for better plotting and alpha band boundary searching
10:Difference←SmoothPSD_EyesClosed-SmoothPSD_EyesOpen
//Calculate the difference of PSD between eyes-closed and eyes-open EEG
11:LeftSideDiff←Difference(1:AlphaPeakFrequency)
//Using alpha peak frequency as the dividing line, extract the difference of PSD on the left side
12:RightSideDiff←Difference(AlphaPeakFrequency:end)
//Using alpha peak frequency as the dividing line, extract the difference of PSD on the right side
11:AlphaLowerBoundary←SearchIntersection(LeftSideDiff)
//Find the intersection (LeftSideDiff=0) which is closest to alpha peak frequency and the corresponding frequency of the intersection is the lower boundary of alpha band
12:AlphaUpperBoundary←SearchIntersection(RightSideDiff)
//Find the intersection (RightSideDiff=0) which is closest to alpha peak frequency and the corresponding frequency of the intersection is the upper boundary of alpha band
13:plot(SmoothPSD_EyesOpen, SmoothPSD_EyesClosed)
//Plot the PSD of eye-open and eyes-closed EEG data
14:**return**(AlphaPeakFrequency,AlphaLowerBoundary, AlphaUpperBoundary)
//Display the results

In the implemented algorithm, the power spectral density $\hat{S}_{NX}(\omega)$ is calculated as follows [15].

First, the Fourier Transform is applied to the input signal,

$$X\left(e^{j\omega}\right)=\sum_{0}^{N-1}x(n)e^{-j\omega n} \tag{1}$$

where $x(n)$ is the input signal, N is the size of the input signal, $\omega=\frac{2\pi}{N}$, and $X\left(e^{j\omega}\right)$ is the corresponding output after Discrete Fourier Transform.

Then, the output of formula (1) is squared and divided by the length of the original signal.

$$\hat{S}_{NX}(\omega)=\frac{1}{N}\left|X\left(e^{j\omega}\right)\right|^2 \tag{2}$$

where $\hat{S}_{NX}(\omega)$ is the Power Spectral Density.

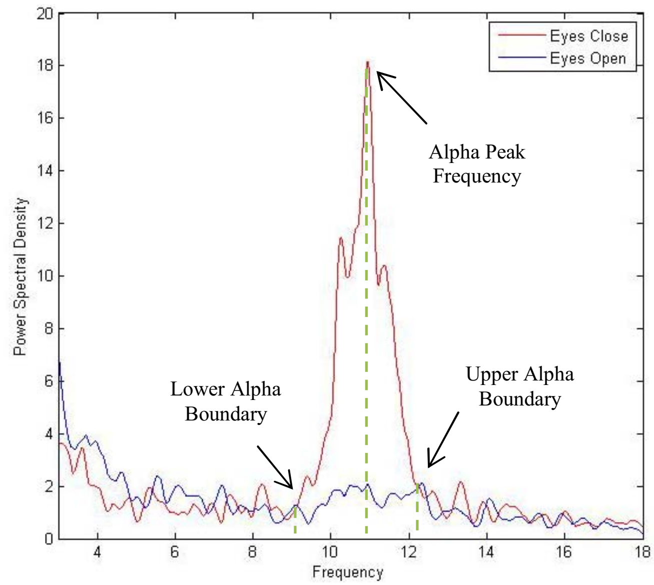


Figure 2. Power Spectral Density of eyes-open and eyes-closed EEG.

IV. Results

In the analysis, 3 subjects' data are excluded as they did not adhere to the test guidelines according to the administrator's observation. Of the remaining 57 subjects', data from two sessions belonging to two of the subjects were discarded as the before-testing EEG was not correctly recorded. As a result, a total of 226 "Simultaneous Capacity" and "Stress Tolerance" scores with the corresponding individual alpha peak frequency are used to study the correlation between alpha peak frequency and performance in the tests (55 subjects x 4 assessment/subject+2 subjects x 3 assessment/subject). The results shows that the alpha peak frequency has a positive correlation with the simultaneous capacity score (p=0.07) and a significant positive correlation with the stress tolerance score (p=0.02) of the Vienna SIMKAP test. The correlation between individual alpha peak frequency and "Simultaneous Capacity", "Stress Tolerance" scores are given in Table I. In Fig. 3 and 4, the linear regression models based on the correlation between individual alpha peak frequency and "Simultaneous Capacity", "Stress Tolerance" are shown. The positive slope in these two figures illustrates the positive correlation between alpha peak frequency and the performance in Vienna test.

TABLE I. CORRELATION BETWEEN INDIVIDUAL ALPHA PEAK FREQEUNCY AND SCORES IN SIMKAP TEST

	Simultaneous Capacity	**Stress Tolerance**
Individual Alpha Peak Frequency	0.12**	0.21*

**: p<0.1; * p<0.05

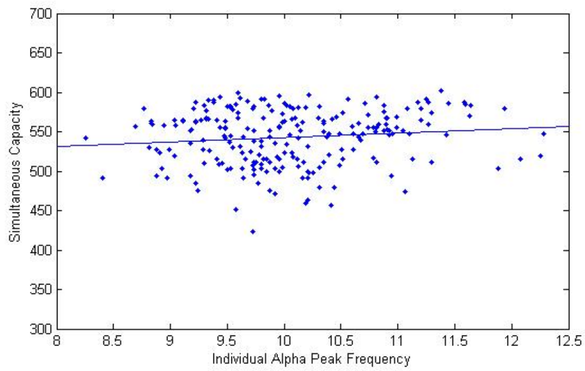


Figure 3. A linear regression model based on the correlation between Individual alpha peak frequency and the simultaneous capacity score.

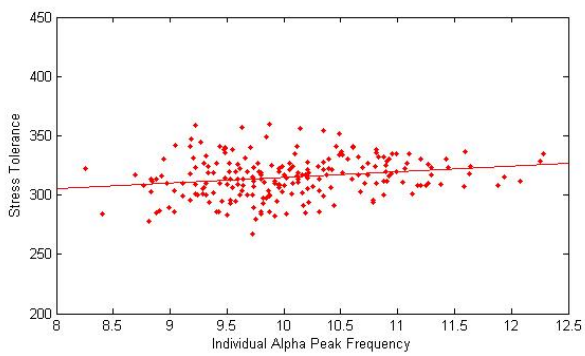


Figure 4. A linear regression model based on the correlation between Individual alpha peak frequency and the stress tolerance score.

V. CONCLUSTION

In this work, we proposed and implemented an experiment with 60 subjects to study how cognitive abilities such as multitasking can be assessed through EEG. We did a preliminary analysis of the experiment data calculating the correlation between the individual alpha peak frequency and simultaneous capacity, stress tolerance parameters of the multitasking test. The results show that individual alpha peak frequency can be used as an EEG-based index/parameter to assess such abilities and predict human performance in multitasking related work. In other words, when individual alpha peak frequency is higher, the performance in the tasks which require simultaneous capacity and stress tolerance abilities will be better. This finding can be used to assess the efficiency of trainings where multitasking ability is targeted for improvement. After training, if the individual alpha peak frequency has increased, this implies improvement in the multitasking ability since the individual alpha peak frequency is a positive indicator of the multitasking ability.

ACKNOWLEDGMENT

The work is supported by Fraunhofer IDM@NTU, which is funded by the National Research Foundation (NRF) and managed through the multi-agency Interactive & Digital Media Programme Office (IDMPO).

REFERENCES

[1] A. Gevins and M. E. Smith, "Neurophysiological measures of working memory and individual differences in cognitive ability and cognitive style," *Cerebral Cortex,* vol. 10, pp. 829-839, 2000.

[2] A. Anokhin and F. Vogel, "EEG alpha rhythm frequency and intelligence in normal adults," *Intelligence,* vol. 23, pp. 1-14, 1996.

[3] W. Klimesch, H. Schimke, and G. Pfurtscheller, "Alpha frequency, cognitive load and memory performance," *Brain Topography,* vol. 5, pp. 241-251, 1993/03/01 1993.

[4] S. M. Suldo, L. A. Olson, and J. R. Evans, "Quantitative EEG Evidence of Increased Alpha Peak Frequency in Children with Precocious Reading Ability," *Journal of Neurotherapy,* vol. 5, pp. 39-50, 2002/01/03 2002.

[5] W. Klimesch, M. Doppelmayr, H. Schimke, and T. Pachinger, "Alpha frequency, reaction time, and the speed of processing information," *Journal of Clinical Neurophysiology,* vol. 13, pp. 511-518, 1996.

[6] O. Bazanova and L. Aftanas, "Individual EEG alpha activity analysis for enhancement neurofeedback efficiency: Two case studies," *Journal of Neurotherapy,* vol. 14, pp. 244-253, 2010.

[7] S. Finnigan and I. H. Robertson, "Resting EEG theta power correlates with cognitive performance in healthy older adults," *Psychophysiology,* vol. 48, pp. 1083-1087, 2011.

[8] P. M. Russo, V. De Pascalis, V. Varriale, and E. S. Barratt, "Impulsivity, intelligence and P300 wave: an empirical study," *International Journal of Psychophysiology,* vol. 69, pp. 112-118, 2008.

[9] G. J. Christie*, et al.*, "Mental rotational ability is correlated with spatial but not verbal working memory performance and P300 amplitude in males," *PloS one,* vol. 8, p. e57390, 2013.

[10] S. J. Troche, R. Indermühle, and T. H. Rammsayer, "Evidence for mental ability related individual differences in the attentional blink obtained by an analysis of the P300 component," *Brain and Cognition,* vol. 78, pp. 230-237, 2012.

[11] B. Ou, C. Wu, G. Zhao, and J. Wu, "P300 amplitude reflects individual differences of navigation performance in a driving task," *International Journal of Industrial Ergonomics,* vol. 42, pp. 8-16, 2012.

[12] L. McEvoy, M. Smith, and A. Gevins, "Test–retest reliability of cognitive EEG," *Clinical Neurophysiology,* vol. 111, pp. 457-463, 2000.

[13] U. Congress, "Office of Technology Assessment: Losing a million minds: Confronting the tragedy of Alzheimer's disease and other dementias," *Pub. No. OTABA-323. Washington, DC: Govt Printing Office,* 1987.

[14] O. Bazanova and L. Aftanas, "Individual measures of electroencephalogram alpha activity and non-verbal creativity," *Neuroscience and Behavioral Physiology,* vol. 38, pp. 227-235, 2008.

[15] A. V. Oppenheim and R. W. Schafer, *Digital signal processing*. Englewood Cliffs, N.J.: Prentice-Hall, 1975