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Age-dependent changes in steady-state visual evoked potentials

[1]Siao-Shi Chin *MEngSc*, [1]Wai-Lai Mah *MEngSc*, [1]Siew-Ying Mok *PhD*, [1]Danny Wee-Kiat Ng *PhD*, [1]Lee-Fan Tan *PhD*, [1]Yin-Qing Tan *MEngSc*, [2]Norlisah Ramli *FRCP*, [3]Khean-Jin Goh *FRCP*, [4]Sing-Yau Goh *PhD*

[1]Department of Mechatronics and Biomedical Engineering, Universiti Tunku Abdul Rahman, Kuala Lumpur; [2]University of Malaya Research Imaging Centre, Department of Biomedical Imaging; [3]Division of Neurology, Department of Medicine, Faculty of Medicine, University of Malaya, Kuala Lumpur; [4]Department of Mechanical and Material Engineering, Universiti Tunku Abdul Rahman, Kuala Lumpur, Malaysia

Abstract

Variability in user performance has been a crucial hurdle that prevents the adoption of brain-computer interfaces (BCIs), but the factors that led to the variations were unclear. This study investigates the effect of age on the strength of steady-state visual evoked potentials (SSVEPs) – an important attribute that determines the BCI performance. Ninety-three subjects ranging from six to 78 years old were recruited for the study, and each of them was tested for their SSVEPs in response to flickering lights of five different frequencies presented at random sequences. The results showed that there is a significant correlation between the strength of SSVEP and user age, with weaker SSVEP response registered in older subjects at all stimulation frequencies tested. Further inter-group comparisons indicated that older subjects tended to show more attenuated SSVEP response compared to the younger and the middle-aged subjects, while there is no significant difference in the SSVEP amplitude between the subjects from the younger and the middle-age groups. The SSVEP response was stronger when elicited using light-emitting diode (LED) compared to liquid crystal display (LCD) stimulators. These findings suggest that age as an important factor in BCI performance, and learning about the age-associated changes could provide additional insight into adapting the BCI system to individual users.

Keywords: Brain-computer interface, steady-state visual evoked potential, age, BCI performance

INTRODUCTION

A brain-computer interface (BCI) is a system that translates users' brain signals into messages or commands.[1] Its original purpose is to enable severely disabled patients to communicate and to control external devices. However, in recent years, it has also been identified as a useful communication tool for moderately disabled patients[2], as well as to aid with the rehabilitation of a specific group of patients requiring advanced neurofeedback.[3-5] Unfortunately, despite of the great potentials, BCIs have not gained sufficient popularity in the clinical settings. One of the most crucial hurdles that prevent the adoption of BCIs is the variability in user performance.[2] Notably, a considerable fraction of BCI illiterate has been consistently reported in the studies involving various BCI approaches over the years.[6-9]

A salient attribute that determines the performance of BCIs is undoubtedly the strength of the electrophysiological signals that are required to drive the system. Accordingly, various efforts have been directed towards enhancing the signal strength, many of which related to the system parameters and designs.[10-12] While these endeavours have led to some encouraging successes, in many cases, it involved extensive testing and customization of a variety of parameters for individual users.[13,14,15] Learning about individual differences, such as age and gender, as well as the various neurophysiological factors that may influence the signal strength[16] is therefore crucial to simplify the hectic yet frustrating testing procedure. More importantly, this could help to increase the chances to arrive at the best BCIs for individual users.

Address correspondence to: Siew-Ying Mok, Jalan Sg. Long, Bandar Sg. Long, Kajang, Selangor, 43000, Malaysia. Email address: moksy@utar.edu.my

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The present study investigates the effect of age on the strength of the steady-state visual evoked potential (SSVEP), a type of electrophysiological signal used to drive the BCI system. Age-associated changes of electrophysiological signals have been widely reported in BCI literature, but many were on other types of signals such as P300[17-18] and mu rhythm.[19] Tomoda *et al*.[20] and Porciatti *et al*.[21] elucidated the relationship between age and strength of SSVEPs, but the studies were based upon signals induced by cathode ray tube (CRT) that is less popularly in use in today's BCI settings. Other studies on SSVEPs used the more common liquid crystal displays (LCDs) or light-emitting diodes (LEDs) as visual stimulators, but focused either only on a single stimulation frequency[22-23] or a small number of subjects.[24] Here we extended the above work by examining the correlation between age and the amplitude of SSVEPs in a large number of subjects in response to a set of stimulation frequencies. In addition to evaluating the effect of age, the difference in the strength of SSVEPs evoked by LCD and LED stimulators was also assessed.

METHODS

Subjects

Ninety-three subjects (64 males, 29 females) aged between six and 78 were enrolled in this study. They were separately recruited from a public exhibition (10th Malaysia Festival of the Mind), a local university, orphanages, as well as the community. A pre-enrolment screening was performed to identify the eligible subjects – only those with normal or corrected-to-normal vision, no prior history of neurological diseases, and no previous experience in BCI were recruited. All the subjects provided informed consent before the start of the study. Permissions were obtained from the respective parents/ teachers/ authorized guardians for children below 12 years old. This study was approved by UTAR Scientific and Ethical Review Committee (U/SERC/06/2016).

Apparatus

Electroencephalography (EEG) signals were recorded using a custom-made acquisition device developed from a 24-bit Delta-Sigma analogue front-end with analog-to-digital converter (Texas Instrument, ADS1299). Electrodes were placed at Oz and the two mastoids behind the ears, with the latter serves as ground and reference. Signals were acquired at a sampling rate of 250 Hz and bandpass-filtered between 2 and 23 Hz.

For the purpose of the current study, two types of visual stimulators were used. The first type comprised of standard LEDs encased in custom fabricated aluminium cylinders with semi-transparent plastics as diffuser. They were mounted on the two sides of the laptop using an aluminium frame. A PIC24 microcontroller was used to vary the frequencies of the LEDs. The second type of stimulator, LCD stimulator is a much simpler construct. Flickering patches of light with different frequencies were generated directly on the computer screen and controlled using DirectX, eliminating the needs for dedicated hardware. To enhance the SSVEP responses, white stimuli and black background were used for both types of stimulators.[15,25] The average luminance intensities for the LCD and the LED stimulators were 207 lux and 620 lux respectively, measured using a light meter (LX-101, Lutron Electronic). Figure 1 depicts the BCI systems featuring the two different types of stimulators.

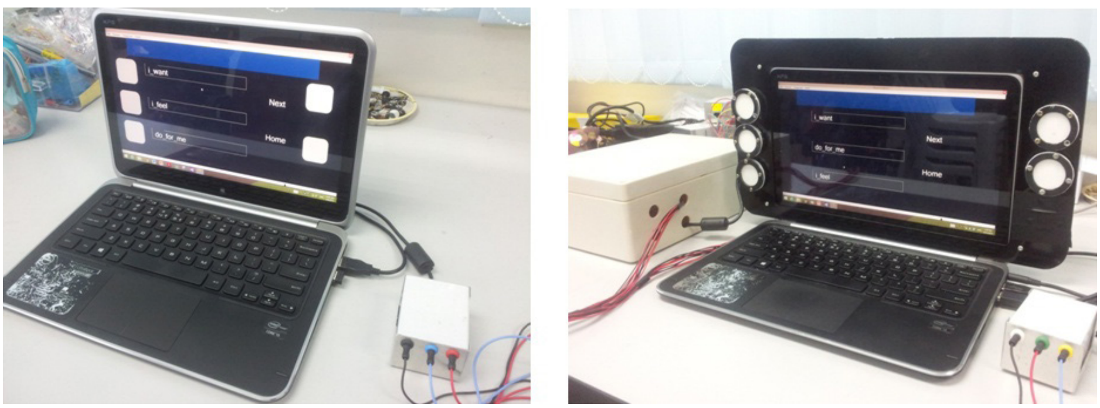

Figure 1. BCI systems. Photographs showing BCI systems featuring LCD (left) and LED stimulators (right). The units on the right of both photos are the EEG acquisition module.

Test paradigm

A BCI test was performed to assess the SSVEPs elicited in the subjects. Each subject was tested for their evoked responses with both the LCD and the LED stimulators. The order of the tests was made random for the subjects to minimize any bias. During the tests, the subjects were seated comfortably in an arm-chair at about 50 cm in front of the BCI system.

The test consisted of 25 trials. One trial lasted for 15 seconds. From second 0 to 5, a cue (blue-colored arrow) appeared on the screen for the subject to get ready of the target stimulus. Subsequently, five squares flickering simultaneously at different frequencies (8, 12, 13, 14, and 15 Hz) appeared. The flickering lasted for 10 seconds and the subjects were asked to focus on the targeted stimulus indicated by the cue. The cue would randomly point to one of the five squares during each trial, five times each for a single stimulation frequency. SSVEP would be registered if the subjects focused on the correct target during the flickering period. The paradigm for the test is illustrated in Figure 2.

Signal Processing

To determine the amplitude of the SSVEPs, the raw EEG signals were first decomposed into individual frequency components using a 1024-point Fast Fourier Transform. This algorithm was performed on every 2-second window at every 0.1-second interval. We then searched for the peak amplitude of the target frequency component within the 10-second flickering period, and take the value as the SSVEP amplitude of a particular trial (Figure 3). Thus, trials with weak or no SSVEP registered would give very low amplitude and vice versa. Trials contaminated by artifacts (identified as signals exceeding ±50 μV) were excluded from further analysis.

The mean SSVEP amplitude, SSVEP for each stimulation frequency is then calculated by averaging the SSVEP amplitude across the five trials.

Statistical analysis

The results from Shapiro-Wilk test showed that the data are non-normally distributed; thus, non-parametric tests were used to assess the effect of age on the SSVEP amplitude for each stimulation frequencies. The strength of the correlation between SSVEP amplitude and age was measured by computing the Spearman rank-order correlation coefficient, (Spearman rho). Kruskal-Wallis test and Mann-Whitney U test using Bonferroni correction were used to make comparisons between age groups. Wilcoxon signed-rank analysis was used to determine the variations in the SSVEPs elicited by the two different types of visual stimulators.

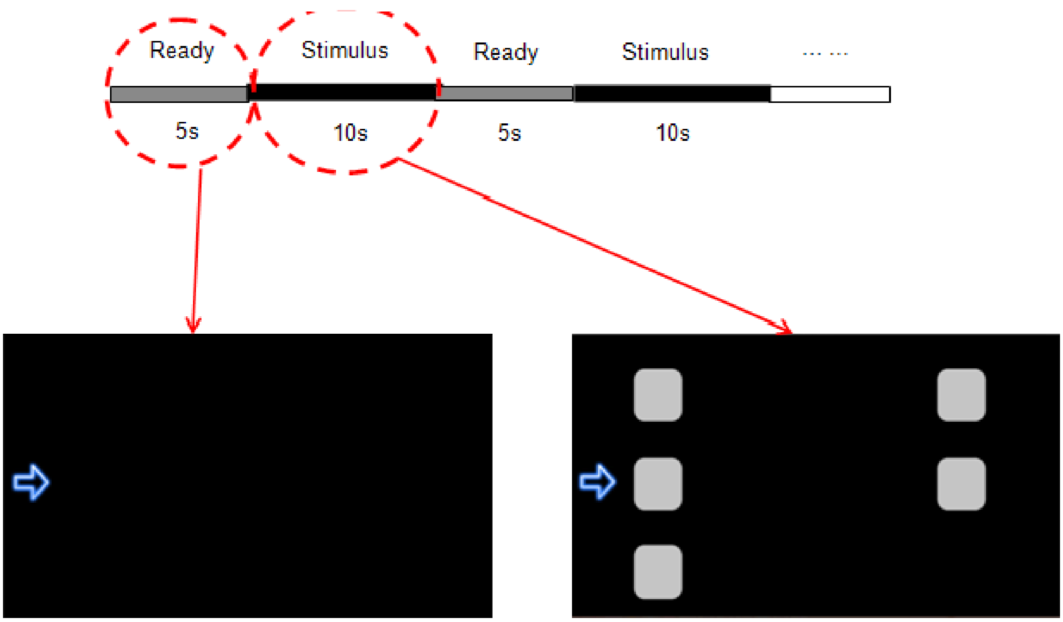

Figure 2. Test paradigm. A trial started off with a ready phase for 5 seconds. A cue is shown during this phase for the subject to prepare for the selection. Flickering squares then appeared for 10 seconds (stimulus phase) and the subjects were required to focus on the one indicated by the cue.

RESULTS

Figure 4 presents variations in the mean amplitude of SSVEPs induced by LCD and LED stimulators as a function of age. We found a moderate negative correlation (r_s~.5) at all stimulation frequencies, indicating that the strength of SSVEPs was related to age. Statistical validation tests confirmed that the results were statistically significant (p<.001).

To investigate whether significant difference exists in the SSVEP amplitude in subjects from different age groups, they were categorized into younger (6 - 19 years old; n = 34), middle-age (20 - 39 years old; n = 31) and older (≥40 years old; n=28) subjects, and their evoked response were compared. The comparisons among the three age groups are illustrated in Figure 5. It is notable that older subjects yielded significantly weaker SSVEP response than subjects from the younger and the middle-aged groups at all five stimulation frequencies, regardless of the type of visual stimulators used (Kruskal-Wallis test, p<.05; Mann-Whitney U-test, p<.0167). The difference between the younger and the middle-aged subjects was not statistically significant, although the younger subjects in general showed stronger SSVEP response than the subjects from the middle-age group (Mann-Whitney U-test, p>.0167).

The comparison of the strength of SSVEPs induced by the two types of visual stimulators was performed by matched-pair Wilcoxon test (Figure 5). The strength of SSVEP response evoked by LED stimulators was significantly larger than that of the LCD stimulators, in agreement with previous studies.[26] Note, however, that the distinction was greater when stimulated using medium frequencies (12 - 15 Hz, p<.001) compared to the low frequency (8 Hz; p<.01).

DISCUSSION

The present study delineates the aging effect on SSVEPs, using a combination of low and medium frequencies that were commonly used in the BCI applications.[27,28] While the variations of the evoked potentials within this frequency range could possibly be caused by modulation of the higher-order cognitive processes such as memory, attention, and emotional responses[22-24], their effects were minimized in our current study that features only passive viewing of the flickering stimuli. Our results reinforced the earlier proposed idea on age-associated changes in evoked potentials[20-21], albeit the level of degradation and the operating principles underlying the changes of the individual frequencies may differ from one another.[29]

The changes in the SSVEP amplitude noted in our current study also indicate that age as an important factor in BCI performance. Indeed, the effect of age on BCI performance has been shown in earlier work in terms of classification accuracy[29], or more commonly information transfer rate.[30] Although these two measures were

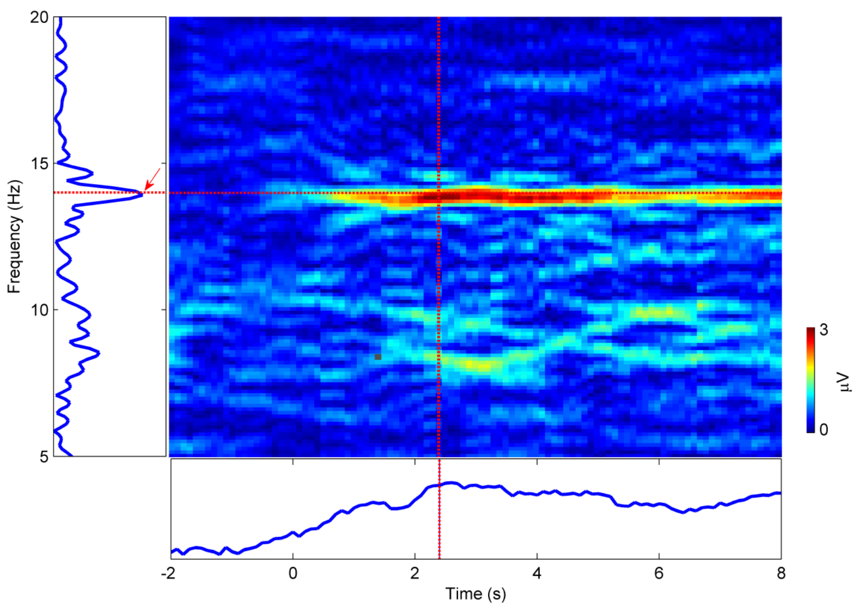

Figure 3. Determining the SSVEP amplitude. Spectogram of EEG signals recorded from a subject in response to 14 Hz stimulation, color-coded according to the bar at right. The arrow indicates the peak of the spectrum, which is taken as the amplitude of the SSVEP of the particular trial.

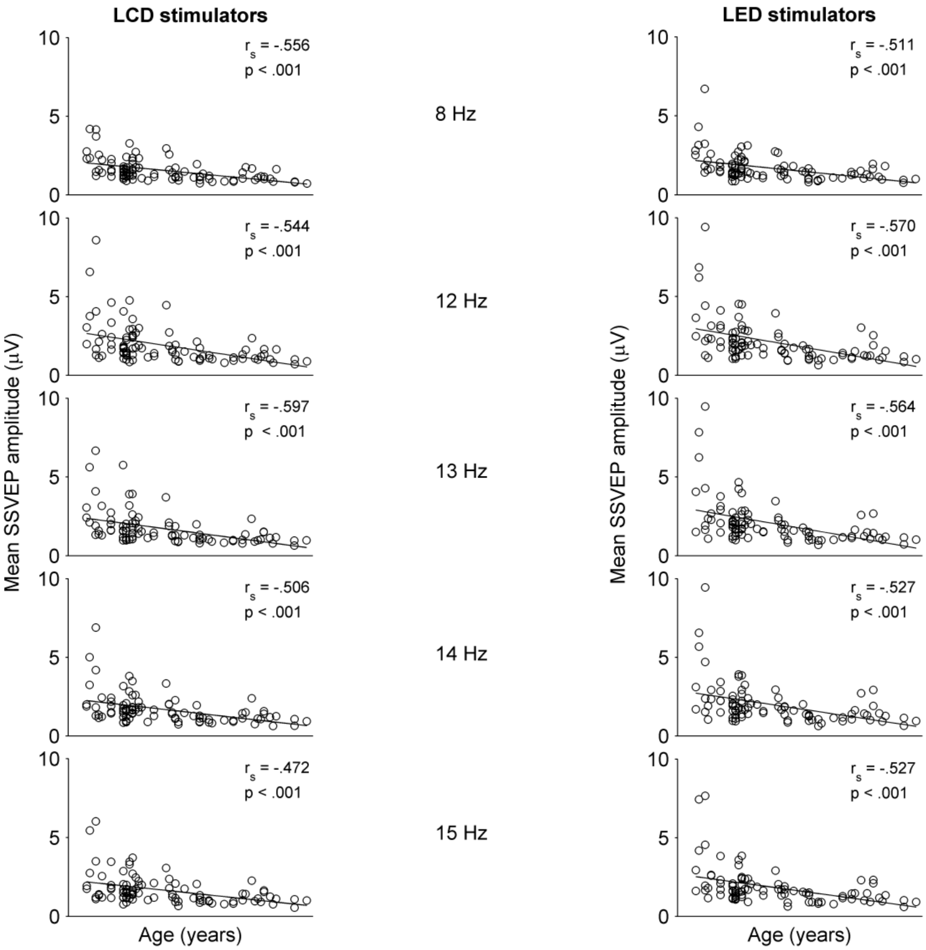

Figure 4. Variations of SSVEP as a function of age. Graphs show data acquired from BCI tests performed using LCD (left) and LED (right) stimulators. Each circle represents the SSVEP from an individual. The regression line for each data set is shown in black.

presented as important indicators of the control ability of the BCI users, they are greatly subjected to the algorithms for the various parameters composing the BCI system, including filtering, artifact removal, feature extraction, feature selection, as well as classification.[31] Understanding how the strength of the evoked potential itself varied with user age could provide additional insight into adapting the BCI system to the users, for example, to find a reasonable estimate of the classification threshold for users of different age range to ease the calibration process.

Degradation of visual sensitivity with age has previously been suggested to account for the decrease in the SSVEP amplitude in older people.[23,24] In fact, visual evoked potentials have been used to determine the visual system loss in clinical assessments of visual function.[32] An earlier study[33] reported that the visual sensitivity in human started to decline at the age of 40, which may reasonably explain why there is a drastic decrease in the SSVEP amplitude in the older subjects above 40 years old in our current study. However, others also postulated that the changes in the visual evoked potentials could possibly be influenced by factors operating outside the retina, including cell death in the neuronal structures involved in the central visual pathways[20], the developmental changes of the underlying neuronal oscillators[29], as well as the decrease in the amplitude of the overall EEG activity.[23] A full understanding of the mechanism underlying the generation of the evoked potentials would certainly require further study.

Comparison of the performance between the two types of visual stimulators showed that LEDs were more effective than LCDs in eliciting SSVEPs, consistent with the previous studies.[26] It

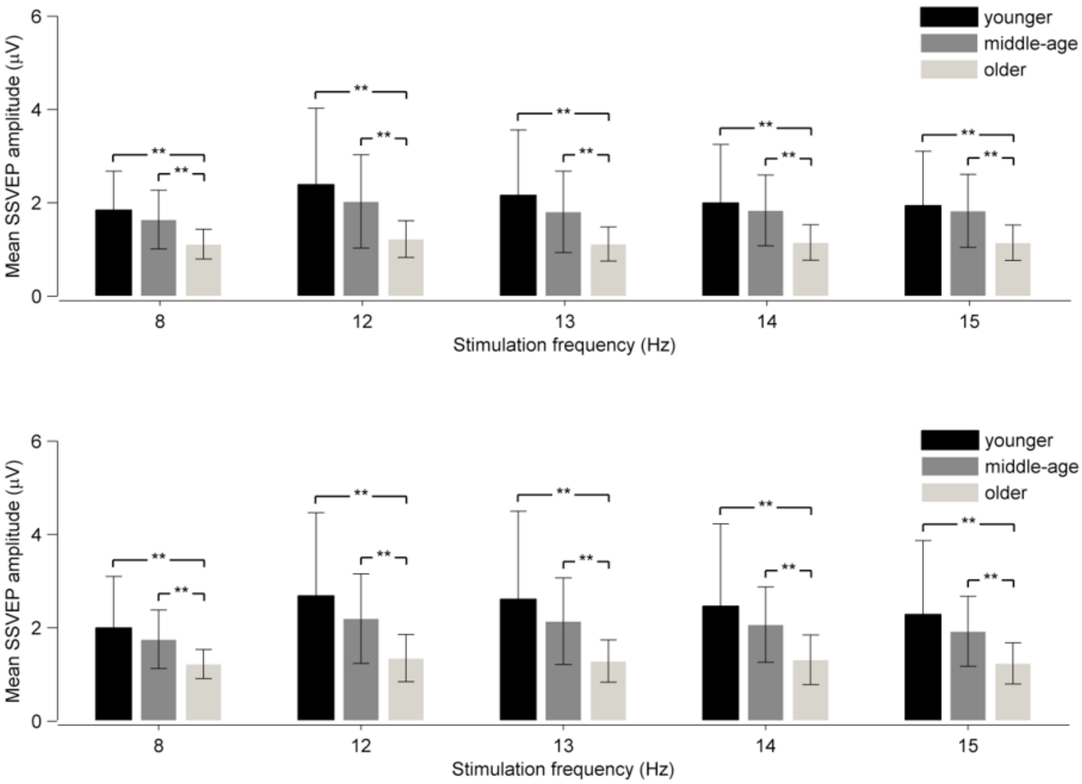

Figure 5. Comparison of SSVEP among three age groups. Results obtained from tests performed using LCD stimulators (top) and LED stimulators (bottom). Error bars indicate the mean and the standard deviations. **indicates statistically significant difference (p<.001) between groups in response to stimulation at the same frequency.

should be noted, however, that the light intensity was not normalized for LCDs and LEDs. LEDs with a higher brightness level were found to be able to induce SSVEPs in some of the subjects, especially older people which did not respond to LCDs at the same tested frequencies. This observation also suggests that LED stimulators are a better choice when considering the applicability for a wider group of people, including those who showed attenuated SSVEP response. The use of LED stimulators in SSVEP-based BCIs could, in part, compensate for the inferiority in the electrophysiological signals caused by aging or other factors, and allow more people to benefit from BCIs.

DISCLOSURE

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Conflict of interest: None

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