Optical Non-Invasive Brain-Computer Interface System

Solomiya Lebid
Institute of Telecommunications, Radioelectronics and Electronic Engineering
Lviv Polytechnic National University, Ukraine
Lviv, Ukraine
solomiya.y.lebid@lpnu.ua

Abstract—The brain-computer interface systems vary due to the purpose of their application. The non-invasive photon counting system approach does not allow broad application of the technology due to its limitations, but can supply necessary information for further developments in this area. Analysis of the visual response investigations using a system of single photons registration with high temporal resolution is described in this article. The system operates in the near infrared area and allows non-invasive functional analysis of the brain. Localisation of evoked responses in the brain due to visual stimulation was performed using electroencephalographic (EEG) system and the photon counting system with frequency resolution. A well-known approach to visual stimulation of the human brain was selected for these studies, which is to revert the chessboard squares of black and white. The stimulus was generated at different frequencies. Image of a chessboard that was generated by a program on the screen and synchronized with the multichannel counter. This allowed analysis of temporal changes in the scattered light from the tissue and correlation with the start of the stimulus. Changes due to the fluctuation of hemoglobin levels in blood flow were observed in the optical signal, which proves the capacity to record changes due to stimulus with the current system.

Keywords—single photon counting system, non-invasive techniques, brain-computer interface, visual stimulation

I. Introduction

Definition of brain-computer interface (BCI) could be formulated in a simple fashion: a system for interpreting signals exchange between a human brain and machine. In modern terms it means communication system between human and computer. Among current applications in medicine, it ranges from prevention to neuronal rehabilitation for serious injuries [1]. The future application possibilities leave medical research and join such fields as education, production, marketing, security, games and entertainment. The only hindrance that such systems had in the past, was luck of affordable non-invasive technology and software to provide reliable solutions for broader applications. Currently technological revolution is overwhelming our capabilities to handle and understand what it offers us and how it changes our life. As for neuroscience research, it is presenting a remarkable opportunity to design and develop flexible and adaptive brain-based neurotechnologies to improve human-system interactions [2]. But an overview of scientific publications today leaves us with the same hope as a decade ago that the near future will allow us to communicate directly with computers and each other.

At least a third of the human cortex handles image processing. The visual perception is passive and requires no extra effort. Though, brain activity during passive watching and reading tasks differs. It was proven that tasks of reading aloud and reading silently engaged the left middle and superior temporal regions of the human brain. Whereas during lexical decision the left inferior, middle frontal cortices and the supplementary motor area of the human brain were engaged [3]. Visual stimulation produces massive response in the visual cortex. It is not surprising that the study of neuropsychology dominates the visual process using different methods [4-8].

The evolution of the neurophysiological equipment in cognitive research is the result of the contribution of various disciplines. It allows us to better understand the function of the human brain on many levels. A non-invasive BCI aimed at studying the relationship of conscious experience with neural mechanisms in non-clinical settings employs commonly used methods based on spectroscopic systems [7-9]. This article examines the system to study of visual perception using advanced photon counter with high temporal resolution. The study was aimed at creating an optical system that allows the signal to be analyzed with high resolution in time.

II. Materials and Methods

A photon counting system described in detail in previous studies [12, 13] uses highly advanced photomultiplier tube in near infrared (IR) field and improved optodes. A response to near-field IR in the living tissue should contain a dual information. Slow response in the visual cortex region at about 5.8 seconds relates to changes in light attenuation due to hemodynamic changes in the cerebral blood volume. This signal is an indirect pointer of the neuronal activity through the neurovascular connection. There is a quick response to stimuli that occurs milliseconds after the stimulus and has to indicate directly the neural activity in visual area due to stimulation [11]. This signal is called an optical signal related to the event (Event Related Optical Signal) [10-12]. Still, there

978-1-5386-2556-9/18/$31.00 ©2018 IEEE

are no reliable methods to register a fast response with non-invasive techniques.

The advanced photon counter records the distribution of photons passing through the tissue in time. Unlike in previous studies, the photomultiplier module H7260A-20 Hamamatsu Photonics KK, characterized by greater sensitivity and linearity in the area range 300-920 nm, was integrated into the system. Also optodes holder design has been improved for better fixation, which allows changing position of optodes quickly. Optodes were located in the visual cortex close to the points O1 and O2.

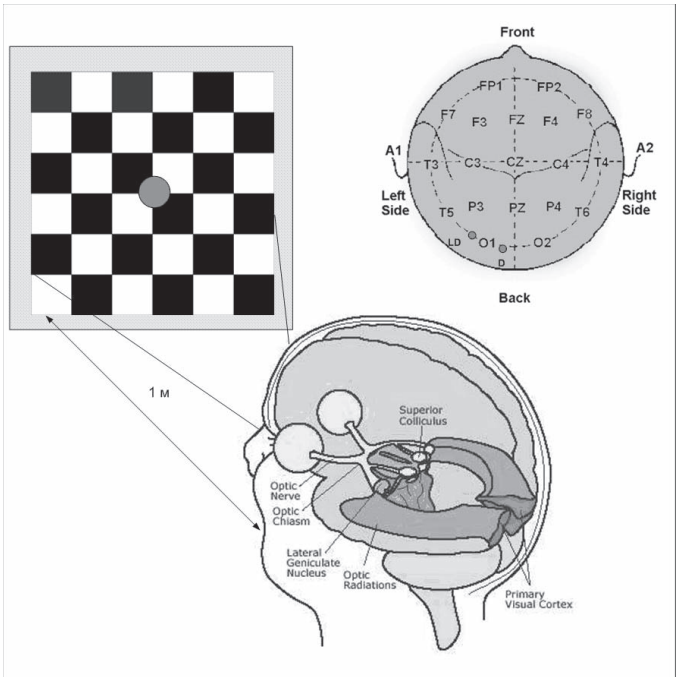

Fig. 1. Schematically represented: a study of visual stimulation electrode arrangement according to system arrangement of electrodes 10-20 and sample location optodes around the point O1.

Electroencephalographic (EEG) system has been applied as well to verify the selected protocol, which allows a better understanding of the reaction to the task of visual stimulation. Data recording system Biopac MP100 with EEG module EEG100C, which allows simultaneous recording electroencephalograms on 16y channels, was employed.

The protocol for visual stimulation is the image of black and white 6x6 chessboard, which is displayed on a monitor. The program generates the image where black and white squares change places periodically with a given frequency. Inside the image red circle is placed as a point of fixation. Tests were conducted at stimulation frequencies 2-21 Hz. Applied stimulation of the full field, meaning the simultaneous stimulation of the left and right visual fields or in other words, a complete image. To investigate the slow response, chessboard changes occur with varying frequency over a fixed period of time - 10 seconds, with a built-in period of rest - 10-20 seconds. The signal recorded by photon counter was analyzed in an independent mode. Measurements were carried out using 780 and 820 nm wavelengths. Slow feedback in the visual cortex has greater amplitude than that, which corresponds to activation of neurons, so it is easier to locate. Optodes are located over the visual cortex as follows: detector on the right over the point O1 (the electrodes arrangement) and source optode 25 mm to the left of the detector. The investigated subject was in a dark room at a distance of 1m from the monitor. The full session on the same frequency lasted 320 seconds. The recording was performed at a measurement frequency of 250 Hz. Research conducted with 7 healthy subjects aged 25-35 years.

III. The results of the study

To eliminate an optode placing problem, an elastic holder was developed. 5 mm diameter collimation lenses were placed on the ends of fiber optic cables to improve signal recording.

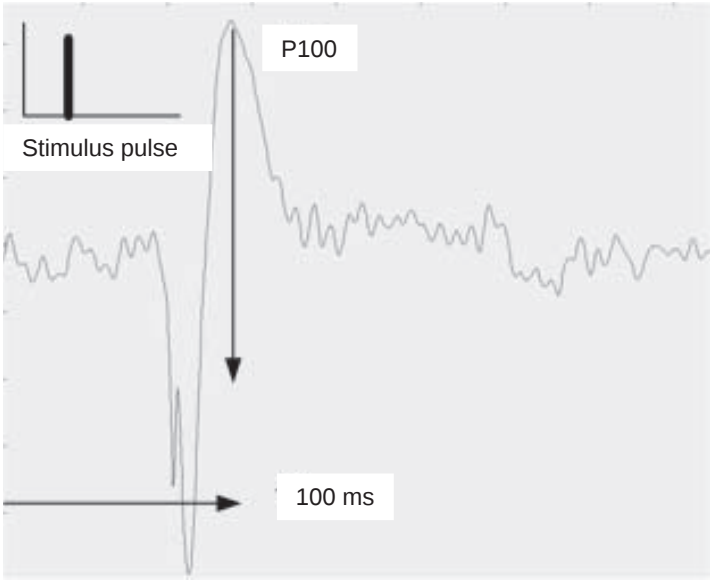

Fig. 2. Potential excited by visual stimulation at the point O1.

First, it was important to verify the correctness of the chosen study protocol. To test the impact of stimulation, chessboard changes occur with a given frequency during the few seconds. EEG signal was recorded at 2 Hz stimulation. Event-related potentials, which are transient characteristics associated with the stimulus, were observed. The repetitive stimulus property in each recorded signal makes the final result very clear. In this case, the visual stimulation averaging was not necessary. Fig. 2 clearly shows the potential due to visual stimulation at the point O1.

Further, it was important to check the photons counting system. As a reference, a recording signal over the point O1 in a dark room with no stimulus was taken. The signal recorded in such conditions makes so-called "zero" line as the optical signal will change due to fluctuations in intra-cranial pressure.

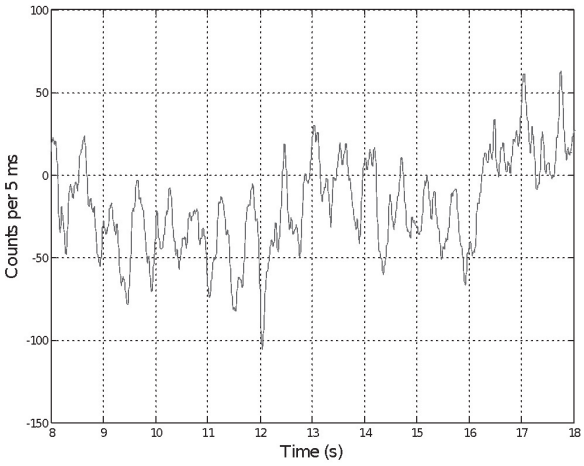

Fig. 3 Optical signal recorded in the point O1 in a dark room, without the influence of the stimulus.

Subsequent studies have conducted a series of tests with the increase of the frequency of chessboard changes. Following a series of experiments, it was decided to choose the frequency of the chessboard changes within 5-20 Hz with steps of 2-5 Hz. EEG and optical signal were recorded simultaneously during the test. The sample recordings are shown in Fig. 4. EEG signal on the left shows that 10 seconds stimulation caused in some cases visually evoked potential, such as stimulation at 5 and 14 Hz. Moreover, there were remaining artefacts in the signal that occur during the rest periods.

The similar optical signal behavior was observed during tests. The frequency of oscillation increased gradually in the optical signal with increasing frequency stimulus. Visible changes in the optical signal related to slow response or changes due to hemodynamic changes in the cerebral blood volume and oxygenation.

In order to get a quantitative assessment of optically registered change, it was necessary to do some offline signal processing, which allowed to calculate changes in oxygenation and deoxygenation of hemoglobin in the blood. Fig. 5 shows the data of oxy- and deoxyhemoglobin calculated from the optically recorded response to stimulus during the 10 seconds chessboard oscillation at 9 Hz and a built-in rest period of 10 seconds. Total testing time was 320 seconds. During this study, the effect of the relaxation to the response to oscillations occurred after 100 seconds after the start of the test and the next 150 seconds.

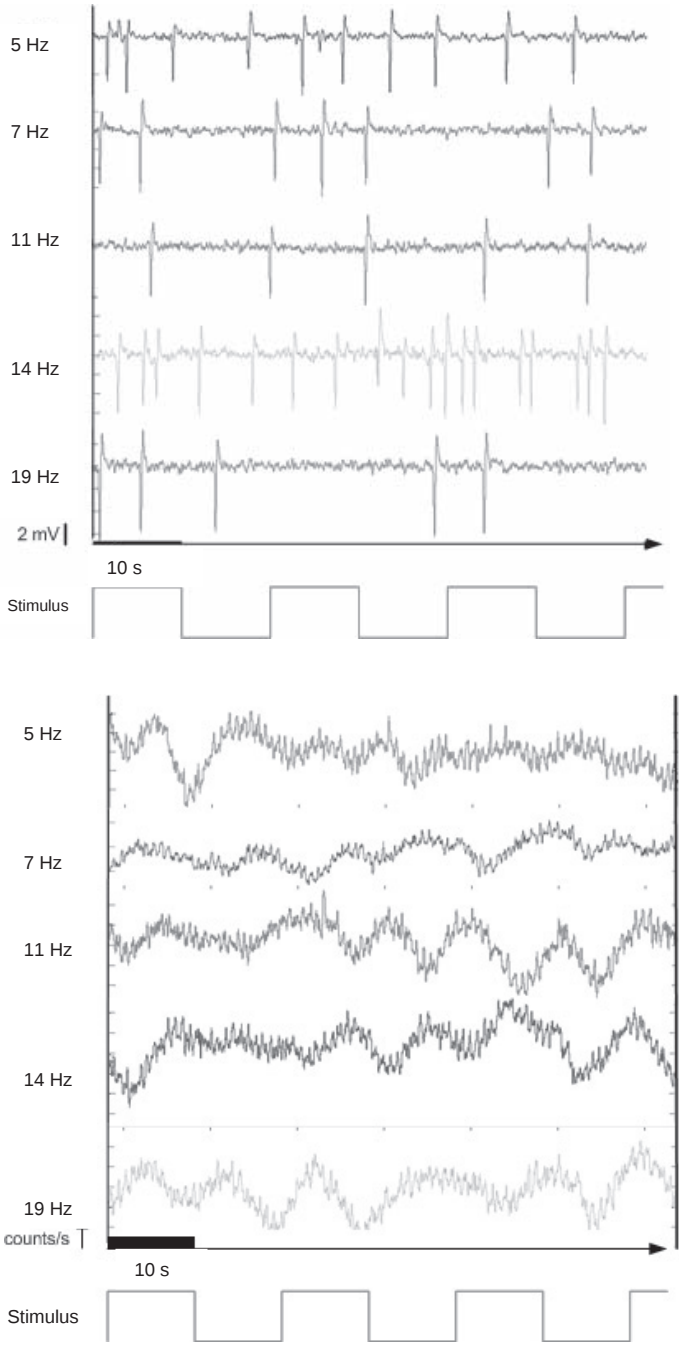

Fig. 4. EEG (above) and optical signals (below) recorded during a series of stimulation.

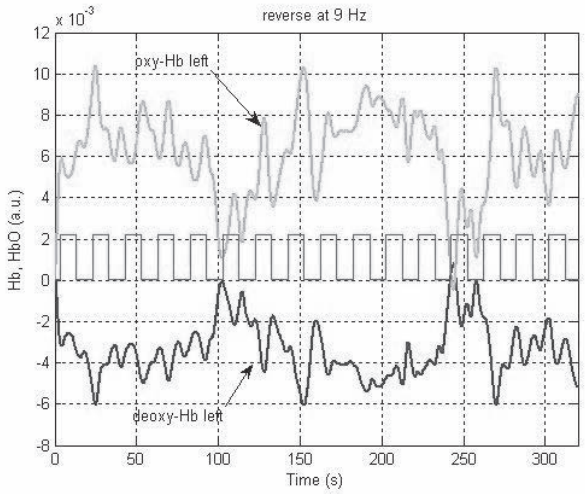

Fig. 5. Estimated changes in oxygenation of hemoglobin in the blood.

IV. Results and Discussion

The results confirm the ability of the photon counting system to register slow changes in the visual area of the cortex in response to visual stimulation. Visual stimulation protocol was chosen because it is believed that the visual stimulation causes the most extensive response in the visual cortex. Since the purpose of the study was to test a new optical system on its suitability for neurophysiological study, tests were conducted on healthy patients.

Application of EEG system allowed to localise evoked responses in the visual cortex. This helped to choose the location for optodes. The problem of real-time estimation of the optical signal is associated with high levels of physiological "noise" during the recording of the signal through the tissue. There were changes observed in the optical signal recorded in dark room conditions which could be caused by intracranial pressure, breathing, etc. Signal artifacts caused by speech and eye movements can be also observed clearly. In order to minimize the level of noise, the object was placed in the car seat, allowing to reduce noise. It should be emphasized that the purpose of these studies was to develop methods to reduce adverse effects on the resulting signal. Studies have provided information on changes in oxygenation due to visual stimulation. Protocols have been developed for a maximum visual response increase within acceptable limits. This was reflected in a clear increase in oxygenation of Hb with repeatability of results for seven of the objects. Observations of the signal change in real time show increase of the signal level due to stimulation and increase of the oscillations allowing to integrate the system into interactive research protocols. However, to obtain quantitative results the signal has to be processed in an offline mode. Also, results showed that the system can be used to create a general picture of slow changes in different areas of the cerebral cortex of the temporal resolution for neurophysiological research. Several pairs of detector-light optodes could be implemented.

The fast response investigation does not show repeatable results. Perhaps new studies with more subjects will allow correlating fast visual response to simulation. However, it is necessary to further develop a method of filtering noise or improve stimulation protocols.

V. Conclusions

The photon counting system created to investigate non-invasively brain responses to visual stimulation can be implemented in laboratory conditions. The aim of the study was to test the application of the non-invasive optical system. The system can reliably record the slow response in the visual cortex corresponding to the cerebral hemodynamic and oxygenation. This factor is sufficient to apply this system in the brain-computer interface but operation requirements and complexity of the system does not appeal to an immediate and broad application.

Similar studies in other laboratories using other optical systems, such as interferometric Near-Infrared Spectroscopy (iNIRS) or functional Near-Infrared Spectroscopy (fNIRS), allow analysis of changes in the polarization in scattered light from the living tissue. Photon counting can analyze the number of scattered photons. Fast signal changes due to the neural activity constitutes 0.05% of the total signal. The approach of averaging the registered responses, similar to the EEG system, in this case, does not bring repeatable results. The number of subjects was not sufficient to obtain the necessary statistics. It is also recommended to develop a filtering approach to eliminate physiological effects on the signal of sensitive optical systems: breathing, heartbeat, alpha waves, etc.

Acknowledgment

The author expresses her deep gratitude to the members of the Bioengineering group at the National University of Ireland in Maynooth and HAMAMATSU Photonics for the interesting cooperation.

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