

# Stimuli design for SSVEP-based brain computer-interface

Marcin Jukiewicz, Anna Cysewska-Sobusiak

**Abstract**—The paper presents a process of stimuli design for SSVEP-based brain computer-interface. A brain computer-interface can be used in direct communication between a brain and a computer, without using muscles. This device is useful for paralyzed people to communicate with the surrounding environment. Design process should provide high accuracy recognition of presented stimuli and high user comfort. It is widely known how to make stimuli for BCI which are using high-grade EEG. Over recent years cheaper EEGs are becoming more and more popular, for example OpenBCI, which uses ADS1299 amplifier. In this article we review past works of other authors and compare it with our results, obtained using EEG mentioned before. We try to confirm that it is possible to use successfully OpenBCI in BCI projects.

**Keywords**—EEG, OpenBCI, SSVEP, BCI

## I. INTRODUCTION

**B**RAIN-COMPUTER interface is a device which allows paralyzed people to navigate a robot, a prosthesis or a wheelchair using only their own brains' reactions. By creation of a direct communication pathway between human brain and external devices, without utilization of muscles or peripheral nervous system, the brain-computer interface makes mapping person's intentions onto directive signals possible.

Brain-computer interfaces (BCI) operate using electroencephalograph (EEG) as measuring device and then through analysis of evoked potentials. One of the phenomena being utilized is SSVEP (Steady State Visual Evoked Potential). That is a reaction that can be observed after a subject was "intently looking" at a stimulus flashing with given frequency. Said frequency is then one of the characteristics of signal recorded above visual cortex. In situation, when the number of stimuli is increased and each of them is flashing with its individual frequency, it is possible to determine which of the stimuli was observed by a subject.

The greatest fault which comes with BCI are financial costs associated with it. Recently interest in cheap, commercially useful BCI devices has risen. One of such devices is OpenBCI, equipped with an ADS1299 amplifier. Producers claim that OpenBCI is sufficient for use in BCI systems. The crucial questions that potential users of such device need an answer to concern stimuli design. Namely, whether OpenBCI allows usage of the same stimuli that had been utilized in other popular systems using known producers EEG, such as g.Tech or BioSemi, or whether the stimuli must be designed specifically with OpenBCI's amplifier in mind.

Autors are with the Division of Metrology And Optoelectronic, Institute of Electrical Engineering and Electronics, Poznan University of Technology, Poznan (e-mail: marcin.h.jukiewicz@doctorate.put.poznan.pl, anna.cysewska-sobusiak@put.poznan.pl).

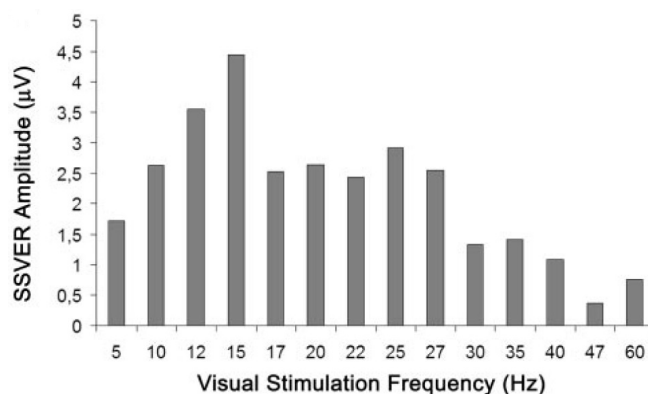


Fig. 1. Mean value of signal's amplitude in SSVEP study versus stimulation's frequency [4]

Depending on color, frequency, signal controlling the stimuli and individual subject, the amplitude of the signal can differ. In order to choose optimal parameters of the stimulus (optimal meaning those which allow for recognition with the highest accuracy) one usually draws on the signal to noise ratio.

First important aspect of designing SSVEP-based BCI is the choice of adequate frequency of visual stimulation. It is believed that bigger signal (with dominant frequency equaling frequency of flashing stimulus) to noise ratio (SNR) ensures greater accuracy of stimulus recognition by AI algorithms [1], [2], [3], [4], [5], [6]. Many publications mention the correlation between SNR and frequency of stimulus' flashing. Those results were obtained from studies in which subjects were presented with stimuli of differing flashing frequencies. Most results gathered from those studies are similar among one another. The most detailed characteristics are presented in Figure 1. It is accepted with reasonable certainty, that the stimuli flashing with frequency of about 15 Hz evokes the strongest reaction in human brain.

Another important aspect during stimulus design is its color. In this case, the studies are not as in accordance with each other, as they were when it came to frequency. The Table 1. contains an overview of studies in which colors of stimuli were analyzed. Colors were chosen depending on differing factors: comfort of the subject, accuracy of classification, value of signal amplitude or signal to noise ratio.

Table 1. shows that the most commonly chosen color is white (4 appearances) and then both blue and green (3 appearances each). Some studies [17], [18] suggest that the stimulus should be bicolored. In mentioned articles it was

TABLE I  
AN OVERVIEW OF RESEARCH ON STIMULUS' COLOR IN  
SSVEP-ORIENTED STUDIES

Article	Analyzed colors	Chosen colors
[7]	white, gray, red, green, blue	white, grey
[8]	white, red, blue	white, blue
[9]	yellow, red, green, blue	green, blue
[10]	red, green, blue	green
[11]	red, green, blue	green
[12]	purple, red, green, blue	purple
[13]	white, yellow, red, green, blue	without decision
[14]	white, yellow, red, green, blue	white, yellow
[15]	white, red, blue	white, blue
[16]	yellow, red, blue	blue, red

proven that using blue-green stimuli improves performance of BCI and is user friendly (does not cause the feeling of discomfort).

The rarely analyzed factor is user's comfort. It is particularly important to consider when designing commercial solutions. The most comfortable stimulus is believed to be the one flashing with frequency significantly above 40 Hz. The reason for this is thus: that kind of flashing is recognized as constant light by human eye, which light, by its nature, is less tiring to watch.

In authors opinion comfort that stimulus color could provide is rather significant. In previously research [19] the subjects claimed yellow to be the most comfortable, followed by green, blue and red. White was marked as the least comfortable color. It is extremely challenging to create one, universal stimulus color, seeing as the level of comfort accompanying each color is individual matter and depends on user's preference.

The appearance and amplitude of possible harmonics in measured signal largely depend on what signal was used to control the stimulus. Usually applied signals are: rectangular signal (with different filling factors), sinusoidal signal and sawtooth signal. It is not unequivocal which kind of signal causes stronger brain reaction: sinusoidal [20] or rectangular with 50% duty cycle [21].

## II. MATERIALS AND METHODS

The sample comprised of 8 subjects. Each one had electrodes placed on the head surface, above the visual cortex, in O1 and O2 localizations, in accordance with international standard 10-20 [22]. Additionally, the reference electrode was situated between working electrodes, in localization Oz, and grounding electrode was placed behind subject ear. All electrodes were connected to EEG. The EEG used was OpenBCI (using amplifier ADS1299, produced by Texas Instruments, and 8-bit control microcontroller Atmega328P and 24-bit analog to digital converter). The device connects to the computer through Bluetooth. The stimuli were generated through microcontroller Atmega328P, which controlled RGB diode, observed by a subject. To acquire signal, original software written in C# was used. The analysis of obtained results was conducted in Matlab environment.

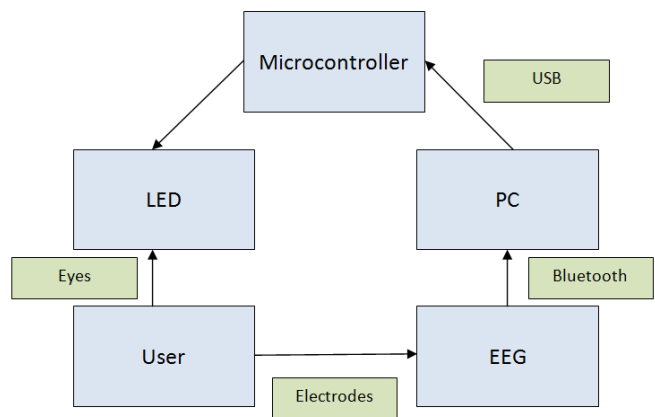


Fig. 2. Block diagram of measurement system [23]

TABLE II  
THE RESULTS OF SURVEY ON COMFORT OF DIFFERENTLY COLORED  
STIMULI' OBSERVATION

	Green	Blue	Red	Yellow	White
Mean	4	3.38	2.63	2.75	2.25

## III. RESULTS

The research was conducted in three stages. The aim of consecutive stages was a choice of one of the stimulus parameters: its color, flashing frequency and generation method.

During first stage each subject was presented with 100 5-second stimuli in 5 blocks. Each block consisted of 20 stimuli. In each of the blocks, stimuli flashed with frequency of 10, 20, 30 and 40 Hz in 5 colors: red, green, blue, yellow and white. The controlling signal was a sinusoid.

The acquired results are presented in Figure 3. and Figure 4. Figure 3. presents averaged results obtained from all subjects. The differences between obtained values of signal to noise ratio for given frequency proved to be rather small.

We ran ANOVA test to check the significant differences between SNR values for all frequencies. We obtained the significance level of  $p < 0.01$ . We also ran Honest Significant Difference Tukey-Kramer test investigate further the differences. In the result of Tukey-Kramer test we consider that there are no significant differences between 10 Hz and 20 Hz as well as between 30 Hz 40 Hz. There are no significant differences between colors for one frequency either.

Moreover, the value of signal to noise ratio should not be the only criterion taken under consideration when choosing the color of stimulus. Comfort is also important and that is the reason why, after the experimental procedure, the subjects were asked to put colors in order: from the most to the least comfortable, assigning points (5 being the most comfortable and 1 being the least). Survey results are presented in Table 2.

We ran Kruskal-Wallis test to check the significant differences between the results of survey on comfort of differently colored stimuli observation. We obtained the significance level of  $p > 0.01$ . There are no significant differences in the results of survey.

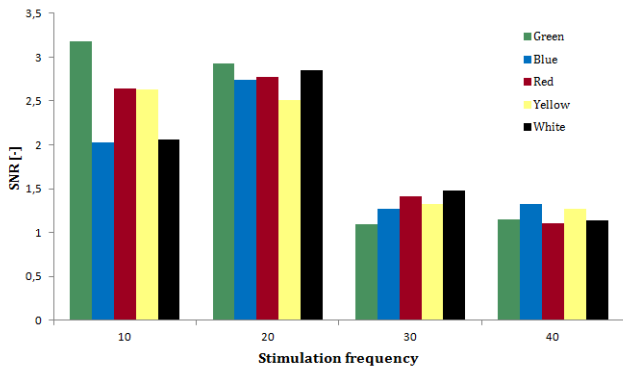


Fig. 3. The signal to noise ratio for different frequencies and colors of stimulation

TABLE III

THE DISTANCE OF POINTS PRESENTED IN FIGURE 4. FROM POINT (0,0)

Color	10 Hz	20 Hz	30 Hz	40 Hz
Green	5.11	4.96	4.15	4.16
Blue	3.94	4.35	3.61	3.63
Red	3.73	3.82	2.98	2.85
Yellow	3.80	3.73	3.05	3.03
White	3.05	3.63	2.69	2.52

TABLE IV

THE RESULTS OF TUKEY-KRAMER TEST. IN EVERY FIELD THE INFORMATION ABOUT SIGNIFICANT DIFFERENCE BETWEEN FOLLOWING COLORS IS INSERTED.

	Green	Blue	Red	Yellow	White
Green	X	NO	YES	YES	YES
Blue	NO	X	NO	NO	NO
Red	YES	NO	X	NO	NO
Yellow	YES	NO	NO	X	NO
White	YES	NO	NO	NO	X

Based on information presented in Figure 3. and Table 2., Figure 4. was created. It shows the relation between value of SNR and comfort associated with given color observation. The best color, that is, the color which causes the strongest brain reaction and at the same time does not bother the subject, should be furthest away from (0,0) point on Figure 4.'s graphs. Calculated distances are shown in Table 3.

We ran ANOVA test to check the significant differences between SNR values for all frequencies. We obtained the significance level of  $p < 0.01$ . We also ran Honest Significant Difference Tukey-Kramer test to investigate further the differences. The results of Tukey-Kramer test are presented in table 4. There are significant differences between Green and Red, Yellow and White. There are no significant differences between Green and Blue, but also there are none between Blue and the rest of colors. So, based on table 3 and 4 we chose Green color to use it in the next stages of experiment.

During the second stage of the study each subject was presented with 105 5-second stimuli in 5 blocks. In each block stimulus was flashing with frequency of every even number in between 8 and 48 Hz. Controlling signal was a sinusoid.

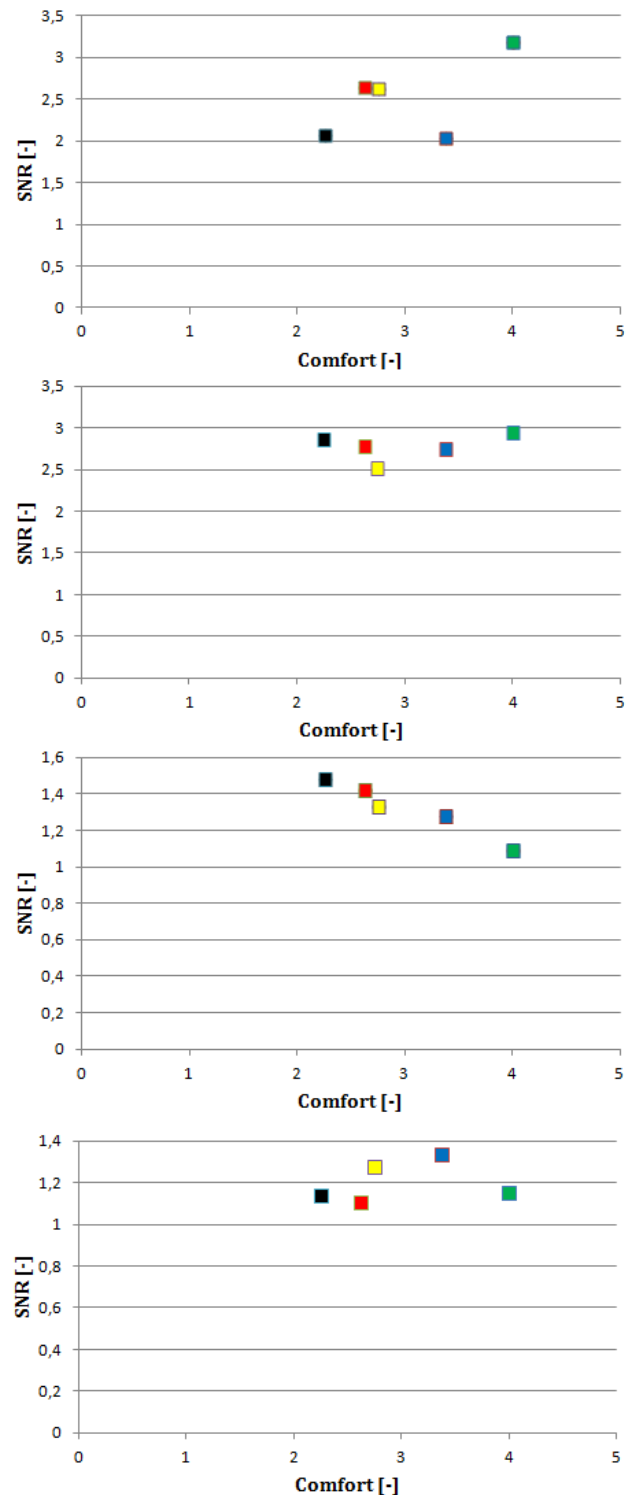


Fig. 4. Value of SNR versus subjects' comfort level for different frequencies: a) 10 Hz, b) 20 Hz, c) 30 Hz, d) 40 Hz

The obtained results are presented in Figure 5. Acquired characteristic matches prior assumptions and the results obtained in other, similar studies, conducted in different research centers. Human brain reaction is the strongest when presented with stimuli flashing with frequency of about 16 Hz. If one required stimuli whose flashing is almost unobservable (or not

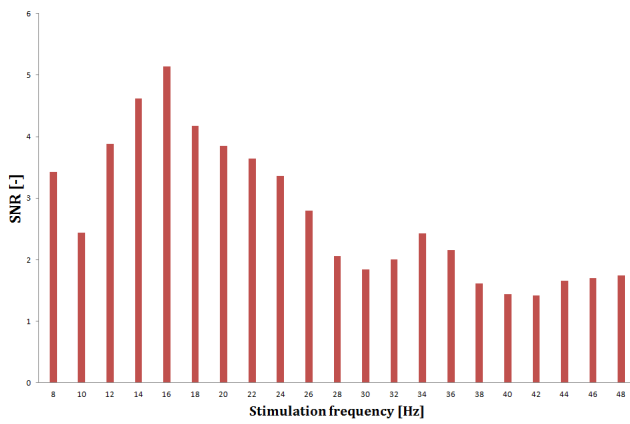


Fig. 5. Value of SNR versus stimulation's frequency

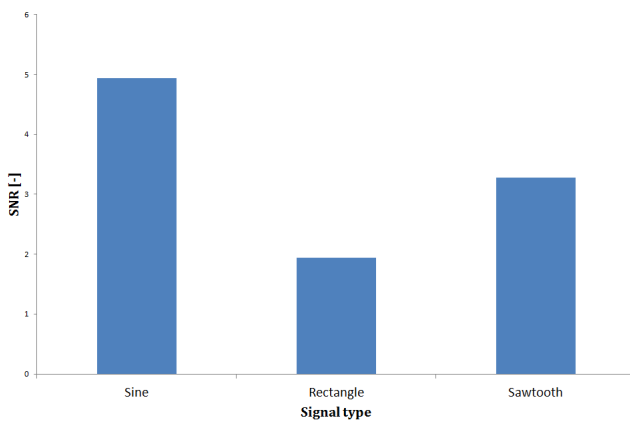


Fig. 6. Value of SNR versus stimulus controlling signal

observable at all), they would be advised to use frequencies oscillating between 33 and 44 Hz.

In the third stage of the study, each subject was presented with 15 5-second stimuli in 5 blocks. Each blocks contained 5 stimuli. In each block, stimulus was controlled by a different signal: rectangular, sinusoidal and sawtooth. The stimulus was flashing with the frequency of 16 Hz and was green colored.

The obtained results are shown in Figure 6. The acquired characteristic is in accordance with prior assumptions. Signal, which causes the strongest reaction in the brain, is sinusoidal signal.

#### IV. CONCLUSION

There is no one refined theory on how the stimulus in SSVEP-oriented experiments should look and with what frequency should it flash. Most of the results of other research centers show that stimulus color should be green or red, which fact we managed to confirm in our own experiment. Obtained characteristic of relation between SNR and stimulus frequency is in accordance with prior assumptions as well. Some differences between obtained results and other studies were derived from analysis of stimulus controlling the signal. In the presented research SNR generated by rectangular signal has lower values, which result is not shared by other research centers.

Presented results partially confirm results obtained in previous studies (value of SNR versus stimulation frequency) and is another input to the discussion about how optimal stimulus (color and signal control) should look. Those who we surveyed complained about the nuisance of the study. This was due to not comfortable color stimulation. Previous studies have focused only on improving the SNR value or the accuracy of BCI. We want to draw attention to the fact that the design of the stimulus should be taken into account comfort-wise. Unfortunately, such an approach sometimes excludes colors that maintain high SNR value. Through parallel analysis of SNR and comfort it has been determined that green is perceived the most friendly color by the users.

Obtained results and their comparison with other scientists research allow us to present the conclusion that analyzed system with ADS1299 amplifier can be used in SSVEP-oriented studies and proves to be promising in the field of BCI applications.

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