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A low-budget stimulation system for evoking SSVEP built on Arduino/Genuino platform

Abstract. *Steady State Visual Evoke Potentials (SSVEPs) are responses of a human brain to outside periodical stimulations. Their particular feature is the fact that the frequency of brain response is the same as the stimulation frequency. This does not mean that SSVEP appears with any stimulation frequency. First of all, the stimulation frequencies evoking SSVEPs are subject-depended, and hence the same stimulation frequency can evoke a prominent SSVEP for one subject, and nothing at all for another one. Second, to evoke the brain response, the stimulus has to be strong enough and has to be delivered with a steady frequency. With brain-computer interfaces (BCIs), using SSVEPs as control signals, often the problem is how to provide a set of stimuli capable of evoking a large number of brain responses. In this paper a proposition of a low cost stimulation system delivering light stimuli is presented. The paper presents both, the structure of the proposed platform and the test results obtained with a real subject. 85 stimulation frequencies from 5 to 31.25Hz were tested during the experiment and for 47 of them the prominent SSVEPs were obtained.*

Streszczenie. *Wywołany potencjał wzrokowy stanu ustalonego (SSVEP) to odpowiedź ludzkiego mózgu na zewnętrzną okresowo pojawiającą się stymulację. Szczególną cechą tego rodzaju potencjałów jest fakt, że częstotliwość odpowiedzi jest taka sama jak częstotliwość bodźca. To nie oznacza jednak, że potencjał SSVEP wystąpi przy każdej częstotliwości bodźca. Po pierwsze, częstotliwości wywołujące SSVEP są zależne od indywidualnych cech badanego podmiotu Po drugie, aby wywołać odpowiedź mózgu, bodźce muszą być odpowiednio silne i muszą być dostarczane ze stałą częstotliwością. Jednym z problemów, który można napotkać w trakcie realizacji interfejsów mózg-komputer wykorzystujących SSVEP jako sygnały sterujące jest właśnie problem dokładnego generowania bodźców w jak największym zakresie częstotliwości. Niniejszy artykuł przedstawia propozycję nisko budżetowego systemu do generowania stymulacji świetlnych, który może zostać zastosowany w interfejsie mózg-komputer. W artykule przedstawiono zarówno sposób budowy systemu, jak i wyniki otrzymane w eksperymencie z rzeczywistym podmiotem. W trakcie eksperymentu wygenerowano 85 sekwencji bodźców o różnej częstotliwości stymulacji (w zakresie od 5 do 31.25 Hz). Dla 47 sekwencji bodźców uzyskano prawidłową odpowiedź mózgu (SSVEP).* ***(Niskobudżetowy system stymulacji świetlnych do wywoływania SSVEP oparty na platformie Arduino/Genuino)***

Keywords: BCI, Brain-computer interface, SSVEP, EEG, Arduino, Genuino.
Słowa kluczowe: BCI, Interfejs mózg-komputer, SSVEP, EEG, Arduino, Genuino.

Introduction

A brain–computer interface (BCI) is a system that transforms changes in oscillatory brain activity into signals used for controlling external devices and applications [1]. In order to fulfil this task, a BCI system first has to identify the predefined patterns in the ongoing brain activity and then convert them to commands sent to the external environment. Although, the brain activity can be measured with a wide variety of techniques, starting from those that directly record the electric and magnetic fields (EEG, ECoG, MEG), and ending with techniques analyzing the local changes in metabolic requirements (PET, fMRI, NIRS), usually EEG devices are used in real applications. There are two main reasons for such a choice. Firstly, they provide a non-invasive recording method, secondly, they do not require substantial financial investments [2].

The EEG signal, acquired in the recording process, has to be then processed with a set of different algorithms to extract potentials chosen to control the external application/device. So far, a lot of brain potentials have been analyzed in order to find those that are stable, easy to induce or control by the user, and possible to separate from the ongoing brain activity in an acceptable time. Currently, most EEG-BCI systems are based on motor rhythms, P300 potential, or SSEP (Steady State Evoked Potentials) - mainly SSVEP (visual SSEP) [3].

The most user-friendly are BCIs based on motor rhythms. Motor rhythms appear in the brain activity, recorded from the motor cortex, when a user perform a motor action or only imagine the performance of this action. Hence, they do not require any external stimuli to be elicited - they are dependent only on the user will. Unfortunately, because of a low spatial resolution of the signal recorded from the skull and close location of the brain areas corresponding to movements of different muscles, the number of commands possible to obtain with this paradigm is rather small [4,5]. Moreover, at the beginning of the work with the interface most users are not capable of eliciting stable motor patterns. Usually, an extensive training is needed before a stable control of the interface is possible. According to Guger et al, with some users such a control is even not possible [6].

Hence, despite of the higher convenience of BCIs based on motor rhythms, more often evoked potentials (P300 or SSVEP) are used in practical applications. Interfaces implementing these potentials provide much more commands (this is true only when the visual stimuli are used) and a higher ITR (Information Transfer Rate) [3]. Moreover, they do not require a user training - usually it is enough to perform the initial calibration of the interface to adopt it to the user's brain activity. Both types of potentials are also easier to extract from the recorded EEG signal that motor rhythms. The main problem with these potentials is that they require constant supply of the external stimuli to be evoked. This is unwelcome for two reasons. Firstly, the stimuli are delivered with a device that has to be located in the user visual field (in the case of visual stimuli) which detracts the user from a real task. Secondly, a constant focus on the stimuli can be tiring for the user which directly translates into a drop in the interface accuracy. Although SSVEP-based BCI is regarded as more tiring, the essential reduction in a control accuracy appear much quicker and is much higher in the case of P300-based BCI. This phenomenon can be explained by different way of emerging both potentials. While P300 needs the direct user attention to be generated, in the case of SSVEP it is enough to observe the stimulus, without engaging the user attention. That is why the SSVEP-based BCI enables a more stable control for a longer period of time.

However, in order to obtain this stable control, one condition has to be fulfilled - the frequencies of the stimuli used to evoke visual potentials have to be matched to the frequencies specific for the given user. Unfortunately, the brain activity is user dependent and hence the predefined set of the frequencies that could be used to evoked SSVEPs for the whole universe of the future interface users simply does not exist. Therefore, in order to successfully control the external devices or applications via SSVEP-based BCI, first the most responsive frequencies has to be identified for a potential user.

One of the devices often used for providing the visual stimuli for SSVEP-based BCI is a computer screen. It is a very convenient approach, since the stimuli are delivered by the same device that is used for displaying the graphical interface of the controlled application/device. With this paradigm the stimuli can be with ease incorporated into the application interface, providing the more natural way of control [7]. This approach, however, has one serious drawback - the number of stimuli flickering with the exact frequencies possible to obtain on a computer screen is very limited. Because of the aforementioned user dependency of the brain activity, it could happen that none of these frequencies correspond to the frequencies specific for the given user. Still, even if all screen-frequencies are recognizable in the user brain activity, the number of possible commands is very small.

Two parameters limit the number of stimuli possible to display on a computer screen: the screen refresh rate and the application used for controlling the displaying process. A computer screen can display stimulations only with frequencies that are integer dividers of the monitor and graphic card refresh rate. If we consider a standard EEG frequency band used in SSVEP-based BCI (5-30Hz) and the standard refresh rate (60Hz), the system displaying the stimuli on the computer screen is capable of providing only 6 different stimuli (at frequencies: 30, 15, 10, 7.5, 6, and 5Hz). The only possibility to expand the number of stimuli flickering with steady and exact frequencies is to use a computer screen and graphic card with higher refresh rate. For example a computer system with refresh rate of 100Hz provides 9 different stimuli (at frequencies: 25, 16.7, 12.5, 10, 8.3, 7.14, 6.25, 5.5, and 5Hz). As it can be noticed, the gain in the number of exact frequencies of the flickering stimuli is rather not high, contrary to the costs which in the case of a computer system with 100Hz refresh rate can be substantially higher.

One way to eliminate those difficulties is to replace exact stimulation frequencies with interpolated frequencies. Such a solution was proposed by Y. Wang et al. in [8]. As they reported in their paper, they were able to display on a computer screen 21 stimuli of different flickering frequency from a very narrow 4Hz band without any synchronization difficulties. Their interpolation method was based on non symmetrical cycles with a varying length of black or white frames. This solution seems to be very interesting since it can give a much wider range of simulation frequencies but it needs further research.

The second issue that limits the number of stimuli possible to display on a computer screen is the software that controls the displaying process. To send stimulations exactly with available frequencies, we have to synchronize the stimuli with frames displayed on the screen. In order to deal with this task we have to use software that will be able to check when each of all 60 frames (in the case of a system with 60Hz refresh rate) is displayed in each second. One of the applications that are capable of performing this task is Psychophysics Toolbox Version 3 (PTB-3). PTB-3 is a free set of Matlab and GNU Octave functions for vision and neuroscience research. It makes it easy to synthesize and show accurately controlled visual and auditory stimuli and interact with the observer [9]. In our work we use the latest available 32-bit version of PTB-3 (Psychophysics Toolbox Version 3for Microsoft Windows, under Matlab 32-Bit, Version 3.0.11 - Build date: Apr 30 2014) since only 32-bit Matlab version supports OpenVibe 1.1.0 [10] that we use to control our SSVEP experiments.

During our previous research we encountered some difficulties with stability and frame synchronization in this environment. Firstly, from time to time PTB-3 was losing frame synchronization in the middle of the experiment what affected the results and enforced restart of the whole experiment. Secondly, during the display, PTB-3 blocked display from OpenVibe (even if we used a second monitor) and we lost any supervision or control over the experiment until it ended. Thirdly, sometimes we had to deal with a sudden drop in speed of flickering pictures. The program did not report synchronization problems but the blinking frequency slowed down.

The second type of device that can be used to provide flickering stimuli is an external provider. The external providers do not suffer from the same restrictions as the computer screen providers. They are able to provide substantially higher number of different stimuli and at the same time they do not have problems with frames synchronization. The aim of this paper is to present a system for evoking SSVEPs composed of such an external provider built on the Arduino/Genuino platform, Matlab scripts used for controlling this provider, and OpenVibe scenario for synchronizing the stimuli with EEG signals. The system was designed as a tool for identifying the frequencies specific for the user's brain activity. However, after increasing the number of LEDs (Light-Emitting Diodes), it can be also used in an on-line BCI mode for controlling the external applications/devices. The number of different stimuli (it is stimuli flickering with different frequencies) that can be delivered by the system is much higher than in the case of a computer screen. It is equal to 85 for the frequency band from 5Hz to 31.25Hz. The paper presents both, the description of the system and also the results of the experiment with a real subject.

The rest of the paper is structured as follows. Section 2 provides the description of the proposed system used for delivering flickering stimuli. In Section 3 the experiment performed in order to verify the practical applicability of the system is described. The next section, Results, deliver the output of the experiment and its analysis. And finally, the paper is summarized in Conclusion section.

Stimulation system

To prepare a low-budget high-frequency resolution stimulation provider we used Arduino/Genuino UNO board. The Arduino/Genuino Uno is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack and a reset button. To program the board via USB we used Arduino 1.6.8 software available on the manufacturer's website and to communicate and send data to/from board we used Matlab add-on dedicated for this board.

In order to emit the stimuli with given frequencies we connected a LED to the board's digital output number 13 and GND. We used only one 5mm LED but it is possible to increase flashing area by connecting LED panel or any other light source powered by 5V and up to 40 mA current/pin. The code that we used to control the stimulation displaying process is given in Fig. 2.

The only task of the code uploaded to the board is to continuously change the on/off status of pin 13. The length of the "on" and "off" periods, the same for both periods, is given in milliseconds and is sent as a parameter named *divider* from Matlab environment (Matlab R2015a). As a result of the changes in pin 13 status, the LED connected to pin 13 flickers with the corresponding frequency until the next value comes from external Matlab program or until the board is turned off. The frequency corresponding to the given *divider* is calculated as: *f=1000/2/divider*, where *f* is the flickering frequency, 1000 stand for 1000ms, 2 is the number of states (on/off) and *divider* is the parameter sent to the board. With this formula we are able to provide 85 different flickering frequencies from the frequency band from 5Hz to 31.25Hz.

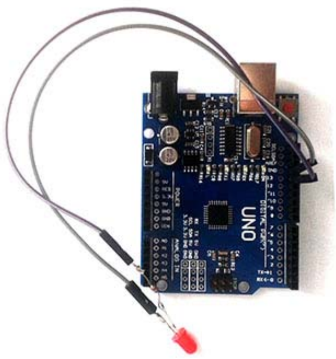

Fig.1. Arduino/Genuino board with connected LED

```
int ledState1 = LOW;
unsigned long previousMillis1 = 0;
int d1hz;
int counter = 0;
const int d1pin = 13;  // the number of the LED pin
void setup() {
    pinMode(d1pin,OUTPUT);
    Serial.begin(9600); }
void loop(){
    unsigned long currentMillis1 = millis();
    if (counter==0) {
    if(Serial.available()>0) {
                d1hz = Serial.parseInt();
                if(sizeof(d1hz) == 0) {
                      d1hz = 0; }
                      Serial.println(d1hz); }
                } if (d1hz == 0) {
                if (ledState1 == HIGH) {
                      ledState1 = LOW; }
                else { ledState1 = LOW;}
    digitalWrite(d1pin, ledState1); }
    else { float interval1 = d1hz;
    if (currentMillis1 - previousMillis1 >= interval1) {
          previousMillis1 = currentMillis1;
          if (ledState1 == LOW) {ledState1 = HIGH;}
          else { ledState1 = LOW;}
          digitalWrite(d1pin, ledState1);
    }}}
```

Fig.2. Microcontroller code responsible for delivering visual stimuli.

Methods

In order to verify the practical applicability of the system described in the previous section, an OpenVibe scenario was prepared. The main task of this scenario was to record EEG signal while LED was flickering with different frequencies. The scheme of the scenario is as follows. The clock stimulator sends the trigger to Arduino/Genuino platform once per thirteen seconds. At the same time an acoustic stimulus is generated to draw subject's attention and inform him that the frequency will be changed. Two seconds later LED starts to flicker with the frequency that has been sent together with the trigger. After eleven seconds the stimulation ends and next frequency is sent from OpenVibe scenario to Arduino/Genuino platform. The frequencies are chosen from the set of possible frequencies (defined in Section 2) in a random order. To give the user time to focus on the stimulus, the first second of stimulation is discarded from the recording. Hence, ten seconds of EEG signal (from 4th to 13th) are saved for each stimulus frequency for further analysis.

The scenario was tested with a male subject, aged 25, right-handed with a normal vision and without any previous mental disorders. The subject was placed in a comfortable chair and the EEG electrodes were applied on his head. In order to limit the number of artefacts, the participant was instructed to stay relaxed and not move. When the subject was ready, the experiment started. Since the whole experiment lasted only 18 minutes and 25 seconds (85 stimulations x 13 seconds), it was conducted in one continuous session. The scheme of the experiment is presented in Fig. 3.

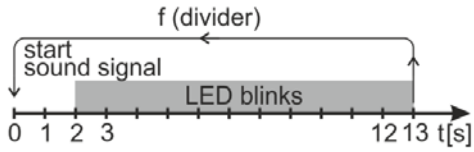

Fig.3. Timing scheme of the experiment. The trial starts with a sound signal intended to draw user attention. After 2 seconds LED starts to blink with a frequency *f(divider)*, where *divider = 16 [31.25Hz] and 100 [5Hz].* The EEG signal is recorded from the 4th to the 13th second of the trial. The same scheme is repeated for all 85 analyzed frequencies.

The EEG data was recorded from 2 monopolar channels at a sampling frequency of 256Hz with a Discovery20 amplifier (BrainMaster). The signal (passive) electrodes were attached to the subjects' scalp at O2 and Pz positions according to the International 10-20 system [11]. The reference electrode was placed at the left mastoid and the ground electrode at Fz. The impedance of the electrodes was controlled with BrainMaster Discovery software and was kept below 5 kΩ.

At the first step of the signal processing stage channel O2 was rereferenced to channel Pz. In this way one bipolar channel was obtained. After this step the EEG data set was composed of 85 signals (one bipolar channel per each stimulation frequency), each containing 2560 samples. Next, EEG data were filtered with a Butterworth band-pass filter of the 4th order in the band 4-35Hz. Then the Power Spectral Density (*PSD*) was calculated separately for each signal with Fast Fourier Transform (FFT).

In order to find out whether our test environment worked properly, we had to analyze the power spectra obtained for all 85 stimulation frequencies looking for the stimulation frequencies that evoked SSVEPs. The decision that SSVEP was found had been taken if:

$$f - b \geq f_{peak} \leq f + b \quad (1)$$

where: f_{peak} - frequency corresponding to *max(PSD)*, f - stimulation frequency, b - buffer around the stimulation frequency set to 0.5Hz.

Results

After an off-line analysis of EEG signal recorded from the subject participated in the test, it occurred that 55% of all stimulation frequencies were correctly recognized. This result meant that using the test environment described in the paper we could built BCI recognizing up to 47 different commands. Of course in practice it would be rather difficult to built a BCI with such a large number of possible choices but this number of correctly detected stimulation frequencies provides us such a possibility.

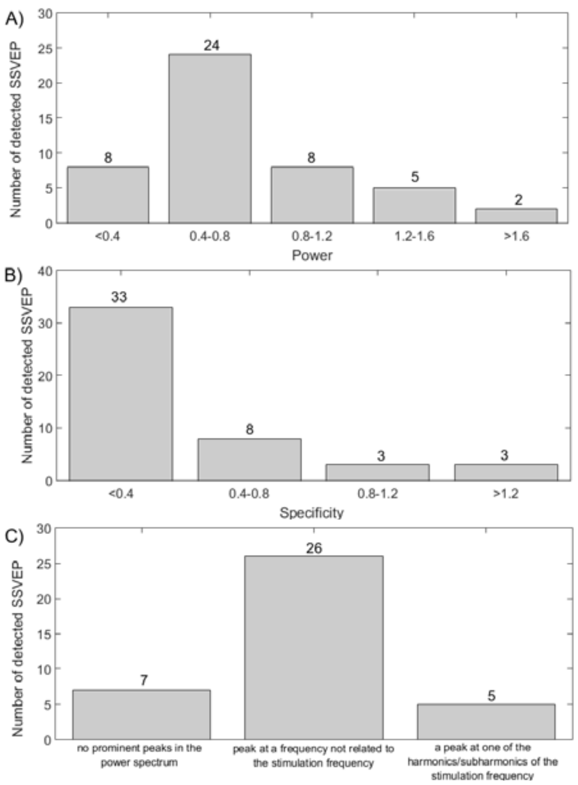

Fig.4. The summary of the analysis of all 85 power spectra; a) The distribution of power of correctly detected SSVEPs; b) The distribution of specificity of correctly detected SSVEPs; c) The structure of "non SSVEP detection" cases.

Table.1. The stimulation frequencies evoking the strongest and the most specific SSVEPs.

Final rank	f	Power	Power rank	Specificity	Specificity rank
1	8,50	1,84	2	1,55	1
2	8,80	1,90	1	1,21	3
3	9,10	1,51	3	1,22	2
4	5,80	1,28	5	1,01	5
5	7,00	1,21	7	1,05	4
6	7,60	1,25	6	0,89	6
7	9,40	1,18	8	0,75	7
8	8,20	0,98	10	0,64	9
9	8,60	0,95	11	0,63	10
10	5,50	0,81	15	0,64	8

Although the goal of our platform was to evoke SSVEPs, we did not limit our analysis only to SSVEPs detection but we analyzed carefully each of 85 power spectra in regard to SSVEP strength and specificity. First, in order to get some knowledge about the quality of the recognized SSVEPs we analyzed the distribution of power of the correctly detected SSVEPs (Fig. 4a). Next, to determine the specificity of the detected SSVEPs, we calculated the distance between the spectral power of SSVEP and the second maximum peak. Since the smaller distance means the smaller probability that the corresponding SSVEP would be correctly recognized in future trials, the SSVEP specificity grows together with this distance (Fig. 4b). Finally, we combined both measures (strength and specificity) to choose 10 stimulation frequencies evoking SSVEP of the highest quality. To deal with this task we assigned two ranks to each SSVEP, one for strength and the other for specificity. Rank no. 1 was assigned to SSVEP of the highest strength/specificity value and rank no. 47 to SSVEP of the lowest value of the corresponding measure. Then, we added both ranks together and obtained the final SSVEPs ranking. Table 1 presents 10 best frequencies together with ranks obtained from both criteria. As it can be noticed in the table all best frequencies, detected for a subject participated in the experiment, belong to a very narrow band of 4Hz (from 5.5 to 9.4Hz). The best result was obtained for stimulation frequency equal to 8.5Hz which has the second highest power (1.84) and the best specificity (1.55).

- Before we ended our analysis, we also scrutinized the stimulation frequencies that did not evoke prominent SSVEPs. The power spectra obtained for those frequencies can be divided into three distinct categories (Fig. 4c):
- no prominent peaks in the power spectrum,
- a peak at a frequency not related to the stimulation frequency,

a peak at one of the harmonics/subharmonics of the stimulation frequency.

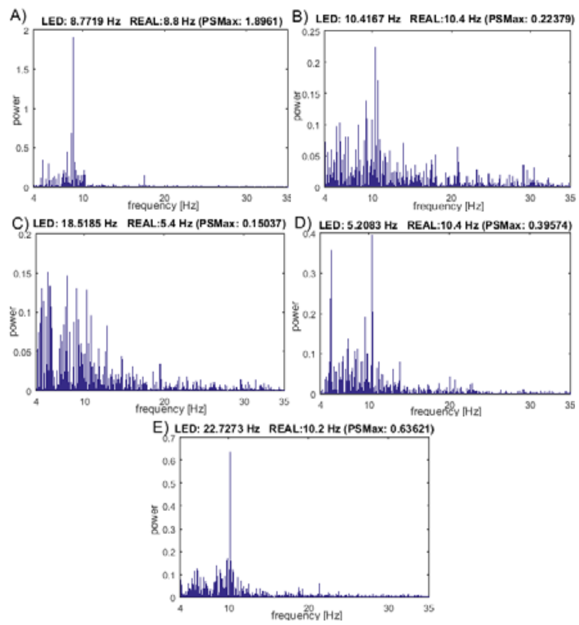

Fig.5. Different types of power spectra: a) SSVEP of a high specificity; b) SSVEP of a low specificity; c) no prominent peaks; d) a peak at a harmonic frequency e) a peak at a frequency not related to the stimulation frequency (peak at 10.2 Hz; stimulation frequency 22.73Hz).

Table 2. SSVEPs found at the harmonic/subharmonic frequencies.

f	Peak frequency	Power of the peak frequency	Specificity	Harmonic
5 Hz	10 Hz	0.352	0.015	1st harmonic
5.208 Hz	10.4 Hz	0.396	0.040	1st harmonic
20.83 Hz	5.1 Hz	0.271	0.052	4th subharmonic
21.74 Hz	5.4 Hz	0.215	0.071	4th subharmonic
31.25 Hz	7.8 Hz	0.233	0.030	4th subharmonic

While the two first categories did not change the outcome of our experiment, the last category did. A peak found at the harmonic of the stimulation frequency is the same valuable SSVEP as the one found at the fundamental frequency. Therefore, 5 SSVEPs detected at harmonic/subharmonic frequencies (Tab.2.) enlarged the number of all SSVEPs from 47 to 52. As it can be noticed in

Tab. 2, both the power and the specificity of newly found SSVEPs were smaller than in the case of the best SSVEPs form Tab.1. Hence, the SSVEPs detected at harmonic frequencies enriched the collection of SSVEPs but did not influence the choice of 10 best stimulation frequencies.

The last figure (Fig. 5) presents 5 power spectra, each belonging to another category: SSVEP of a low specificity, SSVEP of a high specificity, no prominent peaks, a peak at a harmonic frequency, and a peak at a frequency not related to the stimulation frequency.

Conclusion

In SSVEP studies it is very important to deliver repetitive visual stimuli with a precise and stable frequency. Regarding the outcome of the experiment presented in the paper, the system built on the Arduino/Genuino platform is well fitted to this task. In our experiment we delivered 85 stimulation frequencies from 5 to 30Hz frequency band and for 49 of them the prominent SSVEPs were obtained at the fundamental or harmonic frequency.

For our further studies we plan to change the light source from red to white, since the spectrum of the white light is much wider than that of a red light and hence it should stimulate a higher number of cons in retina and produce a more consistent SSVEP response at a higher number of frequencies [12]. Moreover, we plan to extend the frequency range above 30Hz. This should also result in a greater number of observed SSVEPs. Higher frequencies will be also less tiring for tested subjects [13,14].

System based on Arduino/Genuino platform are a very good choice for creating BCI systems for real users. First, they are very easy to design, secondly they are capable of delivering a high number of stimuli with a precise and stable frequency, and thirdly they provide a low-budget stimulation platform.

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