RELIABLE VISUAL STIMULI ON LCD SCREENS FOR SSVEP BASED BCI

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ABSTRACT

A Brain-Computer interface (BCI) enables a direct communication between human and computers by analyzing brain activity. When a visual stimulus with a constant frequency is presented to the user, it is possible to observe a continuous brain response at the visual cortical area. This response is called the Steady-State Visual Evoked Potential (SSVEP) and it can be used for BCI. This paper deals with the methods for creating reliable visual stimuli on LCD screens to evoke SSVEP responses and how to compare them. Three techniques are proposed and compared for the production of stimuli: LEDs, a LCD screen using timers, and a LCD screen using the vertical refresh rate for synchronizing the visual stimuli. The comparison is based on the offline classification of five SSVEP responses. The different visual stimuli were tested with ten subjects. The visual stimuli on the LCD screen based on its vertical refresh rate offer the best recognition rate for the classification of SSVEP responses. The mean accuracy was improved of about 5% thanks to this strategy.

1. INTRODUCTION

BCI systems allow people to communicate through direct measures of brain activity [3]. Unlike all other means of communication, BCIs require no movement. Therefore, BCIs are mostly dedicated to persons with severe disabilities who are unable to communicate through any classical ways [11]. To classify different brain signals, the knowledge of the BCI paradigm guides the solution to some specific signal processing analysis but also to specific applications. For improving BCIs, two main ways have been described and combined. In the first way, the improvement has to come from the signal processing part by using advanced classification and machine learning techniques [8]. In the second way, the improvement has to come from the user by finding some ways to adapt its behavior to the system [10]. Three main kinds of responses are usually used for non-invasive BCI systems: the 300-ms component of an evoked potential (P300) [14], steady state visual evoked potential (SSVEP) [15, 16], and sensorimotor rhythms (SMR), also called "event related de-/synchronization" (ERD/ERS) [13]. Usually the subject has to perform some mental tasks to produce predefined neural activity or to focus on specific external stimulus, *e.g.* visual=SSVEP or acoustic=AEP (auditory evoked potential) [6]). In this work we will focus on non-invasive SSVEP-BCI: SSVEP responses are reliable and good results are reported in the literature [2]. Some researches actually aim at producing better EEG caps, better technologies to facilitate the preparation of the subject and to integrate the BCI easily. One challenge is the quality of the visual stimuli: how to improve the SSVEP response quality. The second common problem: the BCI system must facilitate the integration of the stimuli in the application. In the first section, the different characteristics of SSVEP responses are presented. Different strategies for producing stimuli on LCD screens are described in the second section. The third section deals with the evaluation of the stimuli quality. The experiments and their results are detailed in the fourth and fifth sections.

2. SSVEP RESPONSE

For an SSVEP response, the BCI system must reflect the user attention to a fast oscillating stimulus. The stimuli are flickering lights at different frequencies and their responses in the EEG signal correspond to SSVEP at the same frequencies and their higher harmonics. The best response for these signals are obtained for stimulation frequencies between 5 and 20Hz [12]. Initially the amplitude that characterizes an SSVEP response depends on the frequency, intensity and the structure of the repetitive stimulus. Some works have been done to compare the spectrum differences between LED and monitors [17]. However, no information about the software and the way the frequencies are set, are mentioned. The SSVEP differences are directly related to the frequency spectrum differences of the flickers. According to these differences, the choice of the stimuli is based on the complexity of the BCI system. This property confirms the need of obtain a stable signal for the stimuli. An unstable stimuli spectrum will involve an unstable EEG spectrum in the expected frequencies, which will be a problem for the SSVEP response detection. Different devices can be used for generating such stimuli, we distinguish two types of stimuli devices, which seem be optimized for two types of applications: software used with LCD screen and the device for control of external LEDs.

With stimuli using LEDs, the response is good for most of the subjects. It requires a specific device dedicated to the stimuli. It cannot be used easily with software as the stimuli and the application results are not exactly at the same location. An LED is a simple device that can be inserted in the environment easily; it may be used for ubiquitous computing. Furthermore, LEDs have been successfully used in rehabilitation robotic system like wheelchair control [9]. It is also easier to set an exact frequency to an LED. They can be easily combined to create complex BCIs with many choices. An LED matrix with 48 flickering LEDs was used as stimulator in a BCI [5]. With stimuli on a monitor screen, the graphical user interface (GUI) of the BCI application and the stimuli can be shown on the same screen. This solution is usually more convenient for the subjects. CRT monitor have been widely used for displaying SSVEP stimuli [7]. Although there is no significant difference between the SSVEP evoked by a LCD and a CRT screen, the CRT screen produce more visual fatigue. At the same luminance and modulation depth, the fundamental frequency amplitude in the SSVEP evoked by LEDs stimuli is significantly larger than that evoked by other stimuli from monitors [17]. Thus LEDs may look to be the best choice for a reliable SSVEP-BCI.

3. STIMULI ON LCD SCREEN

The creation of flickering boxes on a LCD screen can be a challenge. We distinguish two main parts: the hardware, *i.e.* the LCD screen, and the software that will produce the flickering boxes on the screen. One interest of the LCD screens is their wide presence; they are low cost common devices, which are not dedicated to BCIs. The characteristics of the screen must not be too specific in order to allow a large audience to use this kind of BCI. LCD screens also allow a more convenient way to create new paradigms for creating BCI.

The stimuli are usually flickering boxes of two colors. Their rendering is not a problem. Nevertheless, the management of the event that switches from one to the other color can be an issue. The notion of frequency implies the notion of time. Fast frequencies require a perfect management and evaluation of the time. One way is to use a real time operating system to handle the time parameters. However, this solution is not a convenient because it is not widely used for building modular BCIs. The classical way is to use common operating systems (OS). However, some considerations regarding the software realization must be taken into account. In addition, Classical OS like Windows are are not real-time operating systems. Thus, problems can be expected for time critical tasks. Although timers are available on windows, their precision for producing precise and regular events can be an issue. However, it is possible to simulate different frequencies over the number of different frames that must be displayed, theoretically up to a maximum frequency equal to the half of the refresh rate. The vertical refresh rate is used as an inner counter for displaying the SSVEP stimuli. Table 1 presents the rendering order of the frames over desired frequencies: 0 represents a frame with a white box whereas 1 represents a frame with a black box. It implied that all the frames must be displayed. The graphic card must be fast enough to render more images than the screen can display. In this case, screen tearing effects can happen. It occurs when the output device sends frames out of sync with the display's refresh rate. Screen tearing can occur on all display types. It is most common with video games, as heavy processing can limit synchronization capabilities but for a simple BCI graphical interface, it is not the case. In addition, the number of frames per second is fixed all the time as the display must obey to a periodic behavior. To solve this problem, the vertical synchronization shall be enabled, which ensures that only whole frames are seen on-screen.

For an LCD screen, the refresh rate is usually 60Hz. Table 1 presents the frequencies that are possible to emulate based on the display's refresh rate. With such refresh rate, it is possible to directly obtain the frequencies: 30.00, 20.00, 15.00, 12.00 and 8.57Hz. It is worth mentioning that the duty cycle is not always equal to 0.5 as the number of frames in one period can be an odd number.

Table 1: The frequencies for a screen with a refresh rate of 60Hz.

Frames	Period	Freq.	Simulated signal
[#]	[ms]	[Hz]	[-]
3.0	50.00	**20.00**	011
4.0	66.67	**15.00**	0011
5.0	83.33	**12.00**	00111
6.0	100.00	**10.00**	000111
7.0	116.67	**8.57**	0001111
8.0	133.33	**7.50**	00001111
9.0	150.00	**6.66**	000011111

Therefore, the choice of the frequencies for an SSVEP-BCI on a LCD screen is limited, but these frequencies are constant. If we According to the usually used frequency band, the frequencies that could involve a good SSVEP response are: 7.50 and 6.66Hz (theta band), 12.00, 10.00 and 8.57Hz (alpha band), 20.00 and 15.00Hz (beta band).

4. EVALUATION METHODS

We distinguish two ways for estimating the signal quality and to evaluate its impact. First, the stability is checked objectively with a specific hardware tool (Frequency Checker (FC) with an oscilloscope). It is possible to get efficient measurements of the produced signal and it ensures the quality of the frequencies. Second, the stimuli quality is checked over the signal processing results (BCI approach). If the stimuli are good, *i.e.* if the frequencies are stable, we may expect a good SSVEP response from the subjects. However, unstable frequencies to some degree may still produce an effective SSVEP response that can be detected.

4.1 Stimuli estimation

The stability of the frequencies has to be checked precisely. The frequencies were checked on the LCD screen with two methods to create the stimuli: the timers, and the display's refresh rate. For frequencies lower than 13Hz, the timers could provide stable results most of the time. However, for high frequencies like 17Hz and above the quality of the signal is bad. The frequency of the stimulus may be stable over few seconds, but the signal is not constant. The frequencies were tested with a separate simple hardware tool, which consists of a photo transistor BP103 as a sensor with a following amplification with BC547 and a digital justification of the signal fronts for easy evaluation of the frequencies with two elements of 4093N.

It is important to obtain a stable signal in a short time period in order to improve the quality of the

SSVEP response. Furthermore, a large number of stimuli on the screen increase the use of the CPU resources, which degrades the quality of the observed signal. While using the refresh rate, all the frequencies are perfectly stable as it was expected. This first analysis clearly shows the improvement of the stimuli quality by considering the refresh rate as a feature for the frequencies choice. Figure 1 presents a visual comparison between the observed signals by the Frequency Checker. Although the frequencies are respected to be good with the timers method, the signal is unstable for 20Hz whereas only some artifacts appear with 15Hz.

4.2 EEG classification

We consider a visual stimulation with a flicker-frequency of f Hz is applied. We use the following description for the signal $y_i(t)$ as the voltage between the electrode i and a reference electrode at a time t:

$$y_i(t) = \sum_{k=1}^{N_h} a_{i,k}\ sin(2\pi kft + \Phi_{i,k}) + B_{i,t}$$

where N_h is the number of considered harmonic. The signal is decomposed into 2 parts. The first part corresponds to the evoked SSVEP response signal, which is composed of a number of sinusoids with the stimulus frequency and a number of N_h harmonics. Each sinusoid is defined by its amplitude $a_{i,k}$ and its phase $\Phi_{i,k}$. The second part of the signal $B_{i,t}$ is the noise, artifacts and all the information that are not relevant to the SSVEP response.

The detection of an SSVEP response on an EEG signal require a time segment for the signal analysis. We consider a time segment of N_t samples of the signals, with a sampling frequency of F_s Hz.

$$y_i = Xa_i + B_i$$

where $y_i = [y_i(1), \ldots, y_i(N_t)]^T$ contains the EEG signal for the electrode i in one time segment. The SSVEP information matrix X is of size $N_t \times 2N_h$. For N_y electrodes, the signal is defined as:

$$Y = XA + B$$

where $Y = [y1, \ldots, y_{N_y}]$ that contains the sampled EEG signals from all the electrodes. A contains all the amplitudes for all the expected sinusoids for all electrode signals.

In order to extract discriminant features from the signal, the signals from the electrodes must be combined. A channel is used for a combination of the signals measured by different electrodes. A vector of channel data is denoted by s. Its purpose is to enhance the information contained in the EEG while reducing the nuisance signals. A channel signal is defined as a linear combination of y_i.

$$s = \sum_{i=1}^{N_y} w_i y_i = Yw$$

Several channels can be created by using different sets of weights. We note N_s the number of channels.

There exists different solutions for the creation of one or several channels. The published neuroscience works provide the information that the SSVEP sinusoids phases vary in relation to the location of the electrodes on the scalp [1]. The goal of the bipolar approach is to obtain a better signal by canceling the common nuisance signals. The Laplacian combination is an alternative to the bipolar solution. In this work, we will consider the minimum energy combination [4]. This method allows the combination of a fixed number of electrodes that cancel the noise as much as possible. The goal of the minimum energy combination is to form combinations of the electrode signals that minimize the nuisance signals. The first step is to remove any potential SSVEP components from all the electrode signals.

The SSVEP signal power estimation is defined by:

$$\hat{P} = \frac{1}{N_s N_h} \sum_{l=1}^{N_s} \sum_{k=1}^{N_h} \left\| X_k^T s_l \right\|^2$$

Let N_f be the number of considered frequencies for the classification. The SSVEP signal power is normalized by N_f.

$$P'(i) = (\hat{P(i)} - \bar{\hat{P}})/\sqrt{var(P)}$$

where $\bar{P}$ is the mean of the N_f signal estimation powers, and $\sqrt{var(P)}$ is the standard deviation of these powers, $1 \leq i \leq N_f$. Finally, we use a Softmax function to normalize these powers into probabilities.

$$P(i) = \frac{e^{P'(i)}}{\sum_{j=1}^{j=N_f} e^{P'(j)}}$$

$$\sum_{j=1}^{j=N_f} P(i) = 1$$

The frequency O is detected if it has the highest probability:

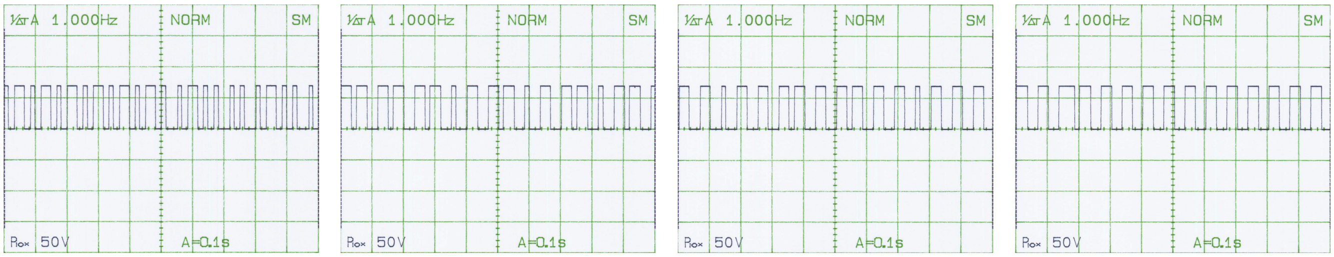
$$O = argmax_i P(i)$$

where $1 \leq i \leq N_f$.

5. EXPERIMENTS

We propose to evaluate the different visual stimuli on the offline classification of SSVEP responses. The five following frequencies have been considered for the experiments: 6.66, 7.50, 8.57, 10.00 and 12.00Hz. The experiment aims at comparing three kinds of display for the creation of flickering boxes:

- (A) A LED.
- (B) A flickering box (black/white) in the center of a LCD screen. The flicker is achieved with multimedia timers.
- (C) A flickering box (black/white) in the center of a LCD screen. The flicker is achieved in relation to the refresh rate of the screen.



(a) 24Hz (b) 17Hz (c) 16Hz (d) 15Hz

Figure 1: Oscilloscope plots acquired by the FC for different frequencies on a LCD screen with the timers synchronization.

5.1 Materials

The non-invasive BCI only uses sensors with contact on the surface of the scalp. In this experiment, 8 standard Ag/AgCl EEG electrodes were used. They are placed on position AF_Z for ground, C_Z for the reference and PO_3, PO_4, P_Z, O_1, O_2, O_Z for the input electrodes on the international 10-5 system of measurement. The impedances below $5k\Omega$ were achieved using an abrasive electrode gel. An EEG amplifier g.USBamp (Guger Technologies, Graz, Austria) has been used for the experiments. The EEG data were acquired with the sampling frequency was 128Hz. During the EEG acquisition, an analog bandpass filter between 2 and 30Hz, and a notch filter around 50Hz were applied in the amplifier. In the first part of the experiment, the red LEDs (4 parallel combined modules HLMP-2685) with the common luminance of around $2.56cd$ were used. For the stimuli display in the second part, a LCD screen of a laptop with the resolution of 1680 x 1050 pixels and a refresh rate of 60Hz was used. The luminance is about $180cd/m^2$ with an estimated contrast of $280:1$. The stimulus is centered on the screen and has a size of 384 x 384 pixels that corresponds to the luminance of about $0.27cd$.

5.2 Protocol

The experiment was carried out with ten healthy subjects. All subjects use a computer screen for their work daily. Half of the subjects possess a SSVEP-BCI experience, they have already used such system for more than one hour. Therefore, such people may benefit from some learning acquired during these previous tests. The average age of the subjects is 27.2 years, with a standard deviation of 2.44. Each subject had to perform a series of trials. During a trial, the subject was advised to look for 20s at one particular stimulus. For each frequency, six trials are recorded. Between each trial, a pause of a minimum of 15s was applied. If after 15s the subject acknowledges a visual fatigue or the need to rest, the next trial was postponed with a maximum of 5min.

6. RESULTS

Without using a BCI, the quality of the produced signals can be checked with an oscilloscope and the FC. The observations on the oscilloscope indicate that the frequencies are correct for every method. However, the signal is not stable for the LCD screen with the use of the timers: the size of the periods vary over time, it is never constant. Although the average frequency is correct, the frequency can vary during the short time period.

Table 6 presents the results for 10 subjects and for the 5 frequencies, the mean, the standard deviation (S.D.) and the accuracy in % for three types of visual stimuli. The EEG signals are classified with a time segment of 1s with the method previously descibed. The classification is performed every 100ms. The accuracy is defined by the number of correct classification by using the method descibed in the section 4.2. The average accuracy for SSVEP stimuli on the LCD screen with the vertical refresh rate reaches 90.35% and 85.26% with the timers' solution. For the LED's, the average accuracy is only 74.46%, although we recall that the luminance of the LEDs is almost 10 times higher than the luminance of the stimuli on the LCD monitor. These experiments display the importance of the SSVEP stimuli and their high impact on the signal detection. The use of the display's refresh rate allows an accuracy improvement of about 5%. The accuracy is not homogeneous between the frequencies. The 12Hz frequency gave always the worst results compared to the four others.

7. CONCLUSION

Two types of SSVEP stimuli were presented. We have showed that the quality of the stimuli is an important criterion for obtaining reliable SSVEP-BCIs. The commonly used timer implementation of visual stimuli can lead to problems. For high frequencies it is impossible to obtain stable frequencies while using timers from a non real-time operating system. The synchronization of the frames on-screen can be used wisely to produce reliable SSVEP stimuli. The main advantages are the possibility to produce many stimuli on the same screen. With this software implementation, it is possible to display an unlimited number of flickering stimuli without concerns about the CPU usage, which can be dedicated fully to the signal processing part. This solution has nevertheless some drawbacks: the number of frequencies that can be produced is limited and depends on the refresh rate of the LCD screen. The frequencies is limited by the screen and cannot be personalized in relation to the user. These results can also be extended to all other situations where SSVEP signals are present. In addition, LCD monitors with a real refresh rate of 120Hz start to be available on the market, *e.g.* for 3D vision.

	6.66Hz			7.50Hz			8.57Hz			10.00Hz			12.00Hz		
	Mean	S.D.	Acc.	Mean	S.D.	Acc.	Mean	S.D.	Acc.	Mean	S.D.	Acc.	Mean	S.D.	Acc.
Method A (LED)															
Min	0.272	0.050	29.80	0.373	0.067	51.80	0.356	0.102	42.40	0.271	0.050	26.20	0.149	0.024	8.40
Max	0.706	0.249	99.70	0.707	0.243	99.10	0.645	0.246	99.30	0.713	0.239	99.50	0.729	0.262	100.0
Mean	**0.551**	**0.169**	**78.20**	**0.513**	**0.189**	**74.59**	**0.505**	**0.187**	**74.18**	**0.538**	**0.159**	**76.43**	**0.501**	**0.179**	**68.88**
S.D.	0.122	0.059	21.14	0.106	0.059	16.53	0.111	0.055	21.72	0.146	0.070	24.20	0.146	0.069	24.15
Method B (LCD with synchronization based on timers)															
Min	0.447	0.045	48.30	0.359	0.035	42.20	0.486	0.028	69.40	0.535	0.009	78.80	0.318	0.027	38.80
Max	0.729	0.224	99.90	0.729	0.247	99.90	0.733	0.215	100.0	0.747	0.228	100.0	0.723	0.254	100.0
Mean	**0.612**	**0.140**	**88.12**	**0.594**	**0.139**	**84.05**	**0.623**	**0.137**	**89.08**	**0.654**	**0.130**	**92.71**	**0.508**	**0.174**	**72.34**
S.D.	0.086	0.062	15.27	0.135	0.076	21.24	0.074	0.056	10.30	0.062	0.075	8.16	0.160	0.087	23.86
Method C (LCD with synchronization based on the vertical refresh rate)															
Min	0.568	0.029	75.80	0.340	0.018	46.80	0.555	0.014	82.80	0.506	0.016	73.20	0.374	0.012	57.30
Max	0.738	0.183	99.90	0.739	0.257	100.0	0.744	0.224	100.0	0.743	0.239	100.0	0.743	0.238	100.0
Mean	**0.656**	**0.107**	**93.46**	**0.617**	**0.129**	**86.15**	**0.661**	**0.106**	**93.45**	**0.655**	**0.115**	**94.14**	**0.577**	**0.149**	**84.56**
S.D.	0.055	0.048	8.022	0.127	0.079	20.35	0.066	0.063	7.35	0.074	0.068	9.210	0.112	0.073	15.78

Such screen will extend the possibilities of SSVEP-BCIs by improving the number of available frequencies to be used as a stimulus on the screen. Thanks to their refresh rate, these monitors will provide a new tool for creating SSVEP-BCI with a large number of flickering objects. This choice will become more judicious for complex BCIs than LED based stimulators.

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