Exploring Multistable Perception to Modulate Steady-State Visual Evoked Potentials using a Computer Graphics Software for a Brain-Computer Interface

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Abstract. *This study investigated the use of multistable perception to modulate steady-state visual evoked potentials (SSVEPs) using a computer graphics program and an LCD monitor. The Rubin's vase ambiguous image was employed for this purpose. A visual stimulator was developed in C++ using the Open Graphics Library (OpenGL). EEG was measured on the occipital area (Oz) of the subject, and a Brain-Computer Interface (BCI) was developed to control a robot in a virtual reality environment. Commands were recognized using the Multivariate Synchronization Index (MSI) method. The results demonstrate the feasibility of eliciting and modulating SSVEP response. During online evaluation, the subject were able to command a virtual telepresence robot with over 80% accuracy and an Information Transfer Rate (ITR) of 7 bits/min.*

1. Introduction

New technologies are emerging to offer individuals with severe motor disabilities an alternative interaction system through brain signals, known as Brain-Computer Interfaces (BCIs) [Yadav and Maini 2023]. BCIs consist of hardware and software components that detect patterns in brain activity, translating them into commands for device control [Yadav and Maini 2023]. Examples of electrophysiological patterns utilized in BCIs include Event Related Synchronization and Desynchronization (ERS/ERD), Steady-state Visual Evoked Potentials (SSVEP), and P300 Evoked Potentials [Yadav and Maini 2023]. Among these paradigms, SSVEP stands out for its high Information Transfer Rate (ITR) and minimal or no need for calibration [Vialatte et al. 2010].

Each command in an SSVEP-based BCI is associated with a visual stimulus at a distinct frequency [Floriano et al. 2019]. When the user selects a command by gazing at a corresponding stimulus, an SSVEP response occurs in the electroencephalogram (EEG), especially from the primary visual cortex (Figure 1). Thus, oscillatory signals can be observed with the same frequency of the stimulus (or its harmonics) [Vialatte et al. 2010]. This response can be observed up to 90 Hz [Vialatte et al. 2010] and three bands can be identified: low ($<$12 Hz), medium (12-30 Hz) and high-frequency ($\geq$ 30Hz) [Zhu et al. 2010]. Nowadays, due to its robustness, SSVEP responses are being widely applied in BCIs to develop assistive technology.

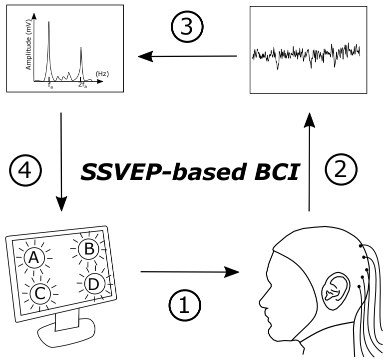

Figure 1. SSVEP-based BCI: 1) Subjects view a flickering stimulus. 2) EEG signals are recorded. 3) Data processing extracts features, e.g., peaks at f_a and harmonics. 4) Features are classified and translated into commands.

Another important feature of SSVEP is that its amplitude can be modulated by attention [Morgan et al. 1996, Mora-Cortes et al. 2018]. A previous work [Tello et al. 2016] demonstrated a binary BCI that allows the subject to modulate the attention in flickering frequencies without requiring eye movements using figure-ground perception. Object recognition is done by means of changes in perception using Rubin's vase illusion. This ambiguous figure is related to the phenomenon called Multistable Perception. This phenomenon is produced by stimuli that are consistent with two or more different perceptual interpretations [Tello et al. 2016].

However, the system was developed using Light Emitting Diodes (LEDs) with a dedicated FPGA circuit, which makes the solution costly. Furthermore, that setup is less flexible and not readily available [Vialatte et al. 2010]. A possible solution is to design a software that generates visual stimuli through drawing of alternated graphic patterns to be displayed on a computer monitor. The challenge with LCD display is because the SSVEP evoked by that device is significantly lower than that evoked using LEDs [Xie et al. 2016], which can degrade the accuracy of BCI.

Therefore, the aim of this paper is to analyse the feasibility to elicit SSVEP through figure-ground stimulus by alternated graphical patterns using a computer monitor. The article follows with an explanation of the materials and methods used for the development and evaluation of the system. Subsequently, some relevant points of the results are presented and discussed.

2. Materials and Methods

2.1. Visual Stimulation

The information exhibited on a computer screen is updated at a defined frequency (refresh rate). For this work an LCD monitor with 60 Hz refresh rate was used. Eq. 1 presents the set of frequencies that a monitor can accurately render using the conventional approach of fixed number of frames per period [Wang et al. 2010].

$$\frac{F}{k}, \quad k \geq 2, \tag{1}$$

where F is the monitor refresh rate, and k any integer number greater than two.

This means that a monitor with a refresh rate of 60 Hz, for example, may exhibit stimuli at 7.5 Hz (8 frames per period), 8.57 Hz (7 frames per period), 10 Hz (6 frames per period), 12 Hz (5 frames per period), and 15 Hz (4 frames per period). The same is not possible for the frequency of 11 Hz, since it would require $\approx$ 5.45 frames per period, which limits the range of possible frequencies in SSVEP-based BCI.

Wang et al. [Wang et al. 2010] proposed a method to use a varying number of frames in each cycle to approximate presentation rates that are outside the limited range of frequencies defined in Eq. 1. The stimulus signal of the specific frequency can be calculated through unitary square wave (Eq. 2). The frames generated square wave (0 and 1) representing the on and off states of stimulus.

$$frame(f, i) = square\left(\frac{2 \times \pi \times f \times i}{F}\right), \quad (2)$$

where f is a required frequency, i is the frame index, and F is the monitor refresh rate.

Based on this method, the visual stimulus program is developed as depicted in Figure 2. The values 1 and 0 denote the on and off states for the vase and faces, respectively. The vase (F_{vase}) and faces (F_{faces}) stimulus signals are combined into four states: '00' (vase: off, faces: off), '01' (vase: off, faces: on), '10' (vase: on, faces: off), or '11' (vase: on, faces: on). Upon each monitor update, the values of the two stimulus signals are analyzed, and the corresponding image is displayed for each state obtained. This allows the development of both stimulation frequencies simultaneously (vase and faces) using only four images. The software employs stimulation frequencies of 11 Hz and 15 Hz, consistent with Tello et al. [Tello et al. 2016].

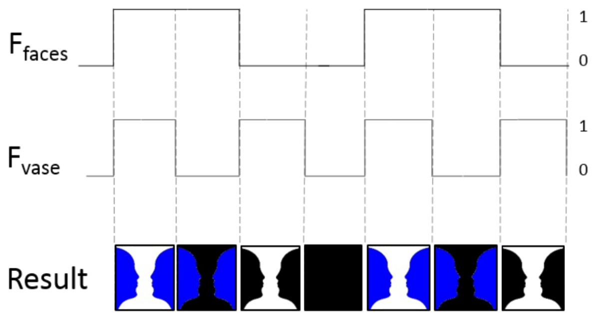

Figure 2. Illustration of the transitions during visual stimulation. The dashed line marks each monitor frame update. At each update, F_{faces} and F_{vase} values are analyzed, determining the displayed image (Result).

The software was developed in C++ programming language and OpenGL library (Open Graphics Library). Through library functions, it is possible to have a complete control over the video hardware, allowing the stimuli to be easily and accurately displayed on the screen.

2.2. Data Acquisition and Signal Processing

The EEG was measured on the occipital area (Oz) with the reference at the right mastoid (sampling frequency of 200 Hz). The ground electrode was placed on the forehead.

The EEG electrode placement was based on the international 10-20 system. A medical equipment BrainNet-36 was used for EEG acquisition.

The EEG was preprocessed using a 6^{th} order Butterworth filter with cut-off frequencies set at 9 and 32 Hz. The filtering process restricts the spectrum of the signal to the range of interest, which contains the fundamental frequency and the first harmonic of the visual stimulus. For frequency analysis, the periodogram of the EEG signals was computed, which is obtained from the Power Spectral Density (PSD) using Fast Fourier Transform (FFT).

2.3. Virtual Environment

Virtual Environment (VE) was developed to simulate the use of a telepresence robot (Figure 3). VE was developed with the Unity3D program. The robot and its movements were built in the open source software Blender 3D. Furthermore, the textures were created using a free license software Gimp. The image presented to the user of the simulator comes from a first person view.

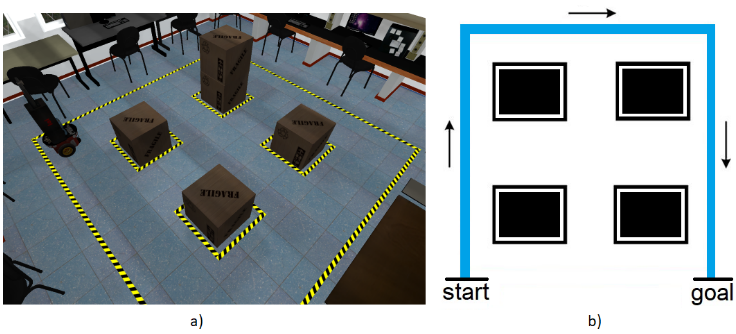

Figure 3. Virtual Environment developed for online tests.

2.4. Evaluation Protocol

The first experiment of this study aimed to analyze the modulation of SSVEP responses using a figure-ground perception-based visual stimulation software. The volunteer sat on a comfortable chair, in front of the computer monitor, 70 cm away from it. He focused his attention on each stimulus (vase/faces) for 12 s. For each step, both stimulus frequencies (11 and 15 Hz) were activated.

For second evaluation, the volunteer performed the route shown in Figure 3, by sending commands to the virtual robot using a BCI. The commands implemented in the system were defined as move a meter ahead, corresponded to the focus attention on the image of the vase, and to rotate 30º to the right when the attention was on the faces. Multivariate Synchronization Index (MSI) [Zhang et al. 2014] applied to a 3 s data length was used for SSVEP classification. The traditional metrics for BCI evaluation such as classification accuracy and Information Transfer Rate (ITR) was used [Vialatte et al. 2010].

3. Results and Discussion

Figure 4 shows the PSD of the SSVEP response elicited by the visual stimuli. The results of the PSDs of the SSVEPs elicited by the visual stimulator were very consistent and accurate. In both situations (faces/vase), each spectrum response contains the peak in

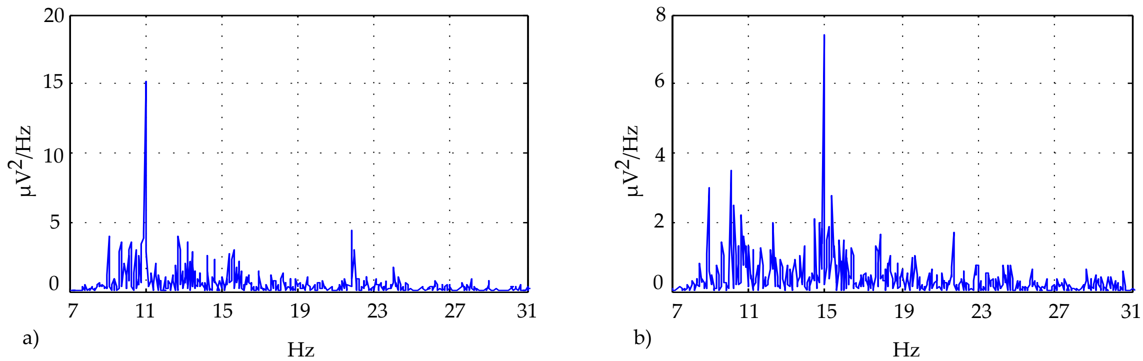

Figure 4. PSD of the SSVEP response elicited by visual stimulation. a) Attention to faces (11 Hz). b) Attention to vase (15 Hz).

the expected frequency. In both cases, the peak of the other frequency was absent in the EEG signal spectrum, even though both visual (faces/vase) stimuli were activated. For online evaluation, the subject was able to perform the proposed task in the protocol with an average of 83.3% of accuracy and ITR of 7 bits/min. The software developed was effective to evoke neural responses, showing that is possible to modulate the amplitude of the SSVEP using a figure-ground perception embedded on LCD screen.

Currently, traditional multi-target SSVEP-based BCIs can be found [Chen et al. 2021]. However, in most cases they are not suitable for subjects with paralysis because the command selection needs neck, head and/or eye movements. To address this limitation, gaze independent approaches based on the attention has been proposed [Cotrina et al. 2017]. Table 1 presents a summary of the characteristics of gaze independent BCI studies.

Table 1. Summary of characteristics of related studies.

Study	Visual Stimulus	Device	Electrodes
Lesenfants et al. (2014)	Interlaced Squares	LED	P3, P1, P2, P4, PO7, PO3, POz, PO4, PO8, O1, Oz, O2
Tello et al. (2016)	Rubin's Vase	LED	Oz
Cotrina et al. (2017)	Luminance	LED	O1, O2, Oz
This work	Rubin's Vase	LCD Monitor	Oz

According to Table 1, the recent studies have used visual stimulation developed with LEDs. As noted in the literature, these stimuli evoke greater SSVEP responses than computer monitors [Xie et al. 2016]. However, this present study demonstrated that an SSVEP-based BCI based on mutistable perception is feasible using a single channel (Oz), with a LCD screen. These results demonstrate that the perception may play an important role in the attention of the subject. Therefore, this new concept of BCI can be used in order to create a link of communication for patients with severe motor disabilities.

4. Conclusion

This work studied the figure-ground perception to elicit SSVEP response using LCD display. The stimulator developed was effective to evoke such responses, showing that is possible to modulate the amplitude of the SSVEP using figure-ground perception on computer monitor. For online evaluation, the subject was able to command the virtual robot and to perform the related task with an accuracy of over 80% and ITR of 7 bits/min.

5. Statement of human rights

This research was approved by the ethics committee under the number CAAE: 44899015.0.0000.5060.

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