A spacecraft game controlled with a brain-computer interface using SSVEP with phase tagging

Ricardo Parafita, Gabriel Pires, Urbano Nunes, Miguel Castelo-Branco

Abstract—**This paper presents a brain-computer interface game that controls a spacecraft that has to avoid obstacles in a space route. The neural mechanism is based on steady state visually evoked potentials (SSVEP) combined with phase tagging. Two flickering stimuli are used to move the spacecraft to left or right. The stimuli are tagged with a phase offset of 180° between them. Phase extraction is applied to narrowband frequency of SSVEP. The stimuli frequencies were selected in a 3-5 Hz range that provides a high level of comfort. The game is being developed to be tested as a neurotherapy tool for children with Neurofibromatosis Type 1, showing attention deficits. Since usability is a major issue in clinical use, the game was designed to be controlled with a single electroencephalographic (EEG) channel, and requiring a calibration time less than two minutes. Pilot experiments were performed with a group of five healthy adults that tested the game, achieving performances above 95% accuracy for 5 second trials.**

Index Terms—**BCI, Game, SSVEP, Phase tag, Neurotherapy.**

I. INTRODUCTION

A brain-computer interface (BCI) is a system that creates a new communication channel based on brain-wave decoding [1]. There are several brain-wave recording techniques, but the electroencephalography (EEG) is the one that enables the most comfortable use of BCI by able-bodied and motor disabled individuals. The portability of EEG devices are leading to a massification of this technology, and consequently, new uses will come up, especially when dry electrodes become a more reliable technology. Currently, wet electrodes still require a 10-15 minutes for subject preparation, which includes scalp cleaning, placement of electrodes and impedance checking. BCI can be a powerful tool to assist people with severe motor disorders in daily tasks, through applications such as communication spellers [2] [3], control of prosthetic devices [4] [5] or systems for mobility [6], [7].

The new type of control provided by BCI interfaces already attracted the interest of the entertainment industry. In coming years this can be a key factor to spread the BCI technology and boost its development because of the economic strength of this industry (electronic game industry had total sales of US $15.6 billion in 2011 [8]). Using BCI games in everyday life can bring huge benefits since it can be used as a neuro-rehabilitation tool for recovery from incidents of stroke and traumatic brain injuries [9], treat seizure disorders or help children and adolescents with attention-deficit and hyperactivity disorder (ADHD) [10] [11]. Moreover, BCI games can also be used by the general population for pure entertainment or to increase their attention skills.

This paper describes a BCI game consisting in controlling a spacecraft. The BCI control is based on phase detection in steady-state visually evoked potentials (SSVEP) with a phase tag. Although this approach is not very common, SSVEP with phase tagging has already been used successfully, e.g. [12] [13].

The game control relies on low-frequency stimuli, within a 3-5 Hz range, causing low eye-strain, which is an advantage compared to other SSVEP approaches. The selective attention demands to control the BCI game can make it a suitable neurotherapy tool for people with attention deficits. In particular, this BCI game is being developed for pilot experiments in a group of children with Neurofibromatosis Type 1. This is a neurodevelopmental disorder, being researched within our group, in which children show cognitive deficits [14]. In the design of a BCI-game for clinical and health applications, important issues should be taken into consideration, such as usability, engagement with the game, and how effective is the game with regard to its clinical goals. This paper is focused on the first two issues.

The paper is organized as follows. Section II presents the state of the art on BCI games. Section III describes the game design and strategy. Section IV presents the methods. A neurophysiologic analysis and the overall results are presented in section V. Finally, section VI draws some conclusions.

II. EEG-BASED GAMES: RELATED WORK

The BCI area has an important role in neuroengineering and it is, eventually, the most visible and popular area of this discipline. Currently, most of the research is focused on exploring neural mechanisms such as EEG rhythms, event related potentials (ERP), SSVEP, and hybrid systems, in order to translate them into commands to control computers and other devices.

Games are the obvious choice when the objective is to capture people's attention [15], in particular if the target are children. Easily, the limitations and difficulties of the player are turned into a challenge that motivates the player, helping him/her to focus on educational or entertainment tasks [16].

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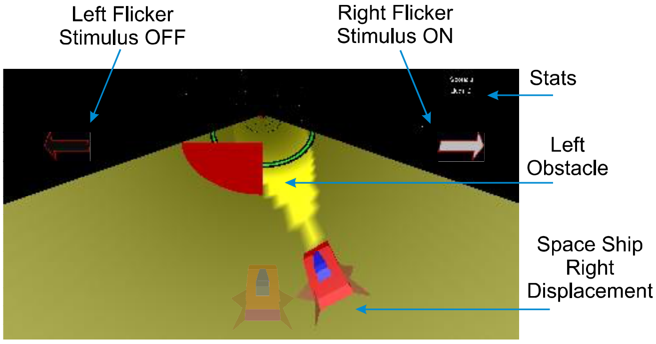


Fig. 1: Screenshot of the game - overlapping of frames containing all graphic elements of the game.

There is already a range of BCI-games running on traditional platforms (consoles and computers). The type of control is still very simple providing a small number of degrees of freedom and low communication rates. Notwithstanding, 2D and 3D games can be controlled effectively, using a variety of neural mechanisms. Just to mention a few:

- **SSVEP -** In [17], SSVEP is used to control four directional arrows (up/down/left/right) to navigate a car in a 2D environment. The same concept is used to control characters such as an avatar through "The Maze" [18] or in strategy games like "Tower Defence" [19] in which defensive structures are placed to defend a tower from waves of enemies with only one stimulus at the bottom-left corner of the screen (flickering at a fixed frequency). SSVEP is also used in immersive 3D game environments, such as the "MindBalance" [20] in which the player tries to maintain the balance of an animated character.
- **Mu rhythm -** In [21], the imagination of motor actions is used to control the movements of a character in a "Tennis" game, through three commands (up/down/stay). Besides videogames, a modified pinball machine controlled with motor imagery is reported in [22].
- **P300 -** Traditionally used in spellers, P300 ERP has already been used in games to select arrows for movement control or to select objects. Some examples are the "Brain Invaders" [23], a modification of the classical space invaders that uses P300 to select the destroyed enemy, or "The MindGame" [24] based on the row-column speller paradigm to move characters across an enlarged chess board.
- **Hybrid -** The neural mechanisms mentioned above can be combined to compose hybrid systems. The "Bacteria Hunt" [25] combines the traditional keyboard with SSVEP and P300 to control an avatar. The "Tetris" game in [26] uses sensorimotor rhythms to move the piece left or right and uses P300 ERP to make the rotation.

Scientific community is increasingly showing interest in BCI for serious games, i.e., games that have pedagogical and clinical components applied to fields as diverse as health, education or rehabilitation. Games are a powerful tool to motivate users during exercises since they transmit the sense of fun during realization of repetitive exercises. Using neurofeedback (real-time feedback of brain-decoding), serious games can be used for diagnosis and rehabilitation of psychological and neurobehavioral disorders such as ADHD [11] or autistic spectrum disorders (ASD) [27].

III. GAME APPROACH

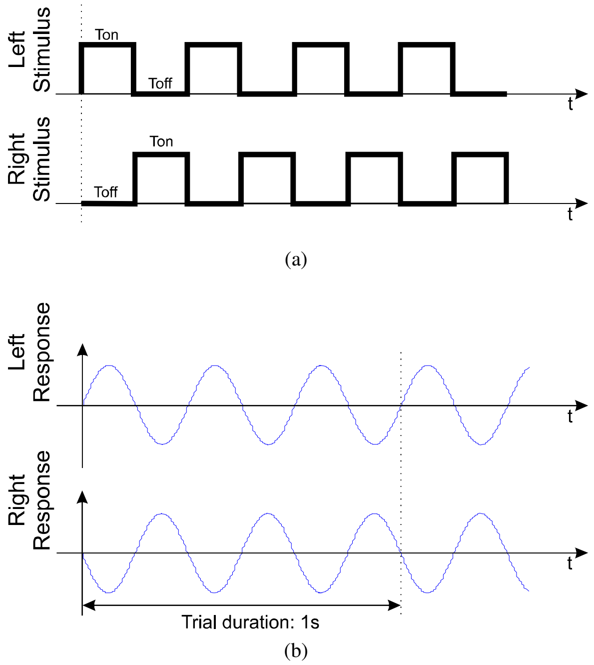
A. *Game architecture and stimuli strategy*

The principle of control of the game, shown in Fig. 1, is based on the combination of SSVEP with phase tagging. SSVEP is widely applied for BCI control due its high information transfer rate (ITR) and high signal-to-noise ratio [28] [29]. Under certain conditions, the SSVEP frequently becomes dominant over the entire EEG, an advantage over other BCI approaches. The proposed algorithm discriminates the phases of the EEG evoked by two stimuli with the same frequency but with an offset of 180° between them. To avoid eyestrain and to allow long periods of use, the frequencies of the stimuli were selected within a 3 to 5 Hz range. Despite SSVEP BCIs are gaze-dependent, in the game this is not an issue for the target population.

The game consists of a spacecraft trying to get to the end of a route in the sky containing obstacles (Fig. 1). The player controls the left/right movements when a new obstacle arises. Figure 1 shows a right movement of the spacecraft to avoid the left obstacle. The two flashing arrows in the left and right sides of the screen are the stimuli used to evoke the SSVEP-phase-tag. At the start of the game, the graphics engine renders the entire world, the spacecraft and the objects in the scenario. After the spacecraft starts moving, the obstacles appear randomly. When each obstacle appears at far, the arrows are displayed without flashing. This gives time for the player to check the position of the obstacle (left/right) and to select the desired arrow, avoiding contamination of the signal by muscular movements (e.g., turn the head or gaze shifting). After a short period, the arrows start flashing. The time until reaching the obstacle is adjusted according to a previous calibration phase. This is the time required for EEG decoding, and depends of the performance of the user. In clinical experiments, this time will be used as a control parameter since it relates to attention. To increase motivation, player can see its score and the remaining lives (shown only before arrows are visible) at the top of the screen. Figure 2a) shows the left/right stimuli generated by a square wave with equal T_{on} and T_{off}. In the example, stimuli have 3 Hz frequency and 180° offset between left and right stimuli. The expected EEG response is shown in Fig. 2b).

B. *System Framework*

For portability issues, the system was designed to require only a laptop and an acquisition system. The EEG signals are recorded with gUSBamp amplifier and the acquisition software uses the C++ application programming interface (API) from g.tec [30]. On the prototyping phase we used also the highspeed Simulink. The graphics library that renders the game's 3D graphics is the OpenGL cross platform which is an open standard.



(a)

(b)

Fig. 2: a) Stimuli generator with 3Hz frequency ($T_{on} = T_{off}$); b) Simulated responses to 3Hz stimulus showing a 180° phase between left and right SSVEP.

IV. METHODS

A. Filtering and phase extraction

To control the game, the algorithm has to detect the phase tag associated with the left and right stimuli. The procedure is illustrated in the diagram of Fig. 3. The EEG signal, represented by Y[n], is filtered by a band-pass filter of third order and 2 Hz bandwidth, and centered on the stimulus frequency. The frequencies outside the region of interest of the filtered signal, $y[n]$, are significantly attenuated. Then, the phase is extracted from $y[n]$ using a correlation measure. Statistical methods such as the canonical correlation analysis (CCA) have already been successfully used in multi-channel SSVEP for phase extraction [12]. However, since we wanted to use a single-channel approach, the phase was extracted in the time domain by a simple measure of correlation between $y[n]$ and a reference signal $r_i[n]$, a methodology which has proved efficient. For each phase lag, a correlation between $y[n]$ and $r_i[n]$ is computed from

$$\phi_i = \sum_{n=1}^{q} |y[n] - r_i[n]| \qquad (1)$$

where q is the total number of samples and $r_i[n]$ is defined by,

$$r_i[n] = sin(2\pi f_c \frac{n}{f_s} + \frac{i\,2\pi}{D}), i = 0, \cdots, D. \qquad (2)$$

The reference signal $r_i[n]$ is generated for different phase lags on $[0\ 2\pi]$ interval and f_c is the flickering frequency, f_s is the sampling frequency, and D is the number of phase lags. The ϕ_i elements compose a vector

$$\Phi = [\phi_0\ \phi_1\ \phi_i\ ...\ \phi_D] \qquad (3)$$

that reflects the correlation values in function of phase lag. The minimum value of Φ is obtained, and the phase estimation $\hat{\theta}$ is given by

$$\hat{\theta} = \frac{2\pi * argmin(\Phi)}{D}. \qquad (4)$$

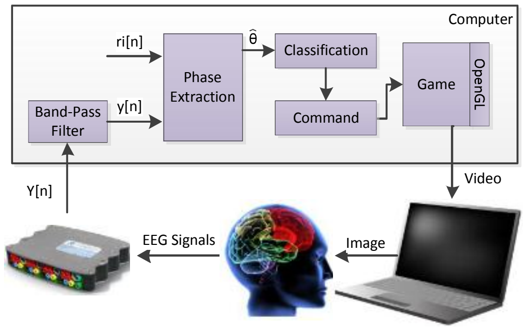


Fig. 3: Workflow and high-level architecture of the BCI game.

B. Participants and experimental setup

Five students from the university campus volunteered to participate in the experiments. Subjects have ages between 22-25 years and do not have clinical problems. The game was played on a regular laptop, with a 15 inches screen. EEG signals were recorded with a gUSBamp amplifier from 12 channels Fz, Cz, CPz, C3, C4, Pz, POz, P3, P4, OZ, PO7, PO8 of the international 10-20 system, using passive electrodes. Ground was recorded at AFz and the reference was recorded from the left or right ear lobe. The EEG was sampled at a 256 Hz rate and pre-filtered with a band-pass filter of 0.1-30 Hz and a 50 Hz notch filter. The impedance of the electrodes was below 10 $K\Omega$.

The experiments were conducted in two stages: training/calibration and gaming stage. During the experiments, users were comfortably seated in a chair in a quiet room of the research lab (see Fig. 4). In the calibration phase, each participant was asked to control the spacecraft in a route with six obstacles, three for each side. For each obstacle, users had to look, for 10 seconds, at the flashing arrow on the opposite side of the obstacle. The duration of the trial time was chosen to ensure stability of the phase, but also to thereafter analyze the evolution of the frequency and phase of the EEG signal. The calibration/training stage took less than 2 minutes, in which a dataset with 3 left and 3 right trials were recorded. A duration of a trial is the time associated witch each left/right detection. During the offline analysis, the trials were analysed with variable lengths to check the minimum time for obstacle detection.

Once the training stage is completed, the user is ready to play the game. The challenge consists in navigating through the route without colliding with the obstacles. The route has 10 obstacles that appear alternately in the left and right side.

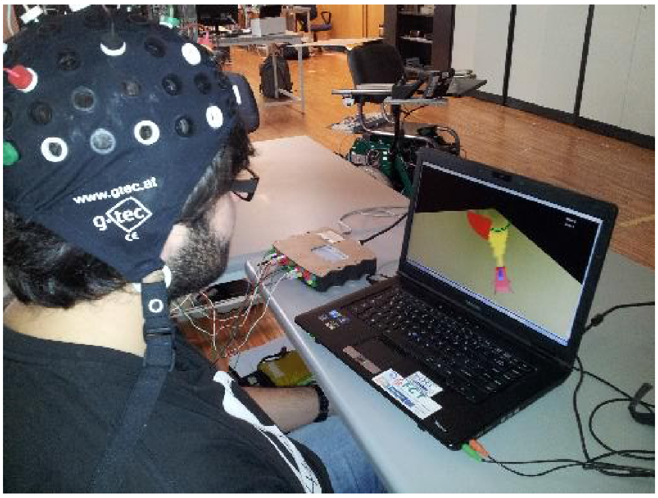


Fig. 4: Participant during an experiment controlling the game.

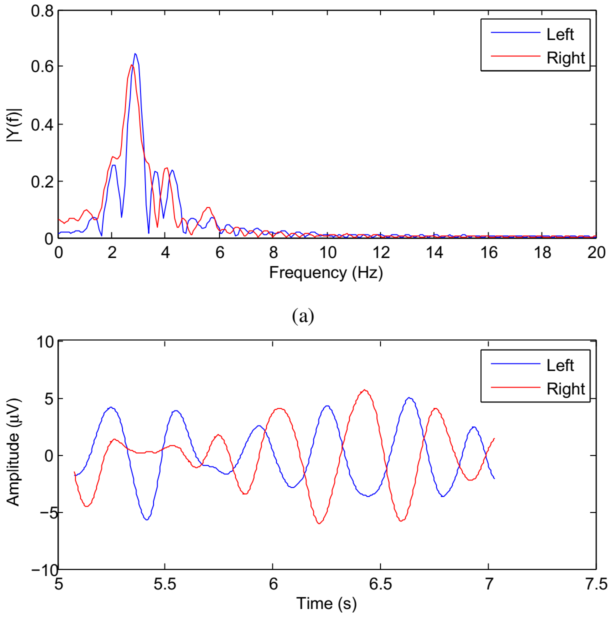
To keep players motivated during the game, the score is increased every time an obstacle is overcome successfully. Several features are being added to increase motivation, such as music and the possibility of having bonus that may be picked by moving the spacecraft. The attention of the player will be tested and challenged by varying the duration of the trials and by triggering disturbing visual events, such as meteorites. The tasks of the game will at a later stage of the project, assess how they can improve sustained visual attention, divided attention, and selective attention of children with neurofibromatosis type 1 showing attention deficits.

V. Results

A. Neurophysiologic offline analysis

Figure 5a) shows the FFT spectra of the EEG signals of one participant at channel Oz after band-pass filtering, using a 3 Hz flickering frequency. The plot shows a peak around 3Hz which means that the response to this stimulus frequency becomes a dominant frequency. Although the responses to stimuli in 3-5 Hz frequency range are not the most discriminative, and in most studies these frequencies are not even considered for SSVEP [31], the results show that they are suitable, being quite comfortable for the user. Figure 5b) shows the signals in the time domain, after band-pass filtering, resulting from the left and right stimuli. After stabilization, left and right responses exhibit a phase difference of 180°, showing that it is possible to rely on phase to distinguish the EEG evoked by the two targets.

Figure 6) shows the phases of the responses of 6 trials, at channel Oz, related to trial duration. This information reveals that during the initial period of stimulation there is a wide variance of the estimated phases, making short periods unreliable for classification. After 3 seconds, the differences between left and right phases increase, the estimated phases start to stabilize and the variance between trials from the same side decreases significantly, making trials greater than 3s reliable for effective classification for this subject.



(a)

(b)

Fig. 5: Analysis of EEG signals of one participant gathered during calibration, at channel Oz, for 3 Hz stimuli. a) Frequency spectra computed with FFT. b) Signals in time domain after passing through the bandpass filter tuned at the frequency of interest.

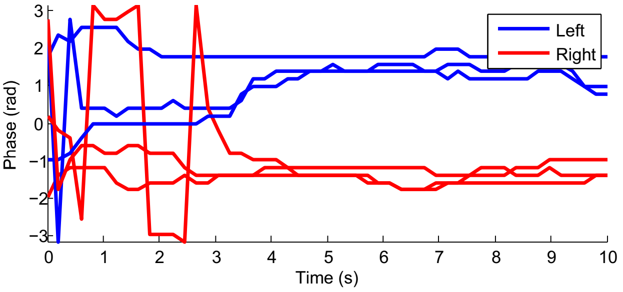


Fig. 6: Phases of 6 trials for one participant (channel Oz and 5 Hz stimuli). Evolution of left and right phases according to trial duration (for 6 trials).

To assess the effectiveness of the proposed approach, an offline classification of training data was carried out. As expected, a higher success rate was verified in channels from the occipital region (PO7/PO8/POz/Oz), since visual cortex actively responds to visual stimuli. The color map in Fig. 7 shows the mean classification accuracy in function of trial duration and channels for all subjects. Accuracies above 90% were achieved when the trial length was above 4s for channel Oz.

B. Gaming and data analysis

After calibration stage, users are ready to control the game. Channel Oz was used for all participants since it showed consistent results for 3 Hz and 5 Hz flicker stimuli during prototyping stage. Notwithstanding, the classification was also

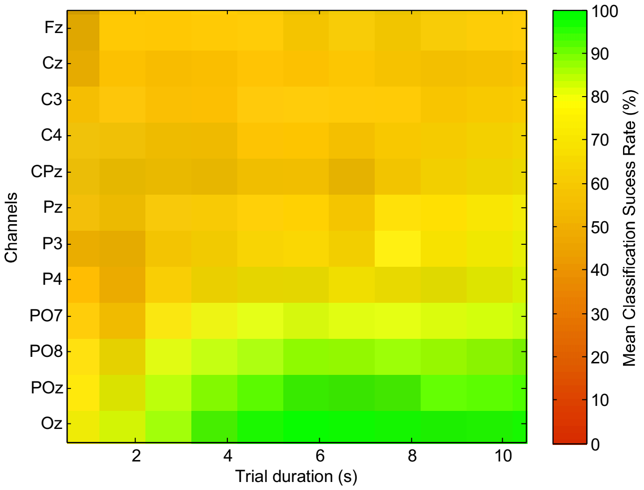


Fig. 7: Color map representing mean classification rates of the training samples in function of trial duration and channels.

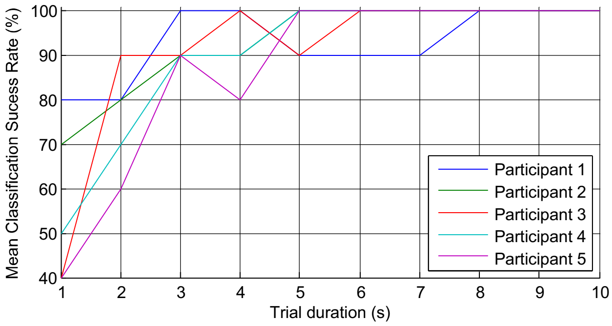


Fig. 8: Mean classification success rate for gaming sessions in function of trial duration.

computed during the game for all remaining channels for comparison. The flicker stimuli were selected from 3 to 5 Hz, according to participant's performance. The game challenge was to control the spacecraft during five minutes under the conditions described in section III-A.

Figure 8 shows players' performance in function of trial duration. The results exhibit a high success classification rate for trials with duration above 5s. Three participants always reached 100% accuracy and the other two have reached this level of performance for trials above 8s. Excluding the idle time between obstacles, the ITR [1] would be of $\approx$ 15 bits per minute (bpm), considering 2 possible selections, an accuracy of 96% and $60/3 = 20$ decisions per minute.

Table I summarizes additional results regarding phase, stimuli frequencies and classification accuracy. Four of the 5 participants controlled the game with 3 Hz stimuli and just one used the 5 Hz stimuli. The average classification results considering a trial time from 3 to 10s is quite significant proving the effectiveness of the approach implemented.

VI. CONCLUSION AND FUTURE WORK

A SSVEP-phase-tag method to control a BCI game is presented in this paper. The results with five participants showed that the proposed tasks have been successfully accomplished by all of them. The classification accuracy was very high for a short trial duration, which can be further improved by refining techniques for phase detection. As major achievements we highlight the requirement of a short time for the calibration session, less than 2 minutes, and the high rates of classification accuracy achieved with a single channel. These are two important requirements to ensure the effective use of the game, in future experiments, by children. The next step will be the validation of the game with a group of healthy children. And finally, validation of the game as a clinical tool in a group of children with Neurofibromatosis Type 1.

User	Freq. (Hz)	Used Ch.	Left (rad) Ph_L	Right (rad) Ph_R	Difference (rad) $\lvert Ph_L - Ph_R \rvert$	Mean Success Rate (3-10s in %)
1	5	Oz	2.99	-0.71	2.58	96.25
2	5	Oz	1.47	-1.32	2.79	97.50
3	3	Oz	-2.68	1.10	2.49	97.50
4	3	Oz	-1.85	0.80	2.65	97.50
5	3	Oz	-2.60	1.18	2.49	96.20

TABLE I: Summary of results in gaming sessions for all participants.

ACKNOWLEDGMENT

The authors would like to thank to all participants, who volunteered to do experiments, from the Institute for Systems and Robotics, University of Coimbra (ISR-UC) and from the Institute of Biomedical Research on Light and Image (IBILI). This work was supported by the Portuguese Foundation for Science and Technology (FCT) and COMPETE Program (grants RIPD/ADA/109661/2009 and PTDC/SEN-TRA/099413/2008).

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