Navigating in virtual worlds using a self-paced SSVEP-based Brain-Computer Interface with integrated stimulation and real-time feedback

Jozef Legény* Raquel Viciana Abad† Anatole Lécuyer‡

Abstract

An open question in research nowadays is the usability of Brain Computer Interfaces (BCI) conceived to extend human capabilities of interaction within a virtual environment. Several paradigms are used for BCI but the Steady-State Visual-Evoked Potential (SSVEP) stands out as it provides a higher information transfer rate while requiring less training. It is an electroencephalographic response detectable when the user looks at a flickering visual stimulus. This research proposes a novel approach for SSVEP-based BCI controller used here for navigation within a 3D virtual environment. For the first time the flickering stimuli were integrated into virtual objects as a part of the virtual scene in a more transparent and ecological way. As an example, when navigating inside a virtual natural outdoor scene, we could embed the SSVEP flashes in the wings of virtual butterflies surrounding the user. We could also introduce the use of animated and moving stimulations when using SSVEP-based BCI, as the virtual butterflies were left with the possibility of moving and flying in front of the user. Moreover, users received real-time feedback of their mental activity and were thus aware of their detected SSVEP directly and continuously. An experiment has been conducted to assess the influence of both the feedback and the integrated controller on navigation performance and subjective preference. We found that the usage of a controller integrated within the virtual scene along with the feedback seems to improve subjective preference and feeling of presence, despite of reducing performance in terms of speed. This suggests that the novel approach whereby we propose to integrate feedback and flashing stimuli in virtual worlds in an ecological way could spread in the community and could change the way we design SSVEP- based BCI for virtual environments.

Published in Presence: Teleoperators and Virtual Environments
http://dx.doi.org/10.1162/PRES_a_00075

*Inria Rennes, France, jozef.legeny@inria.fr
†Telecommunication Engineering Department, University of Jaén, Spain, rviciana@ujaen.es
‡Inria Rennes, France, anatole.lecuyer@inria.fr

1 Introduction

One of the main advantages of Virtual Reality (VR) is the opportunity that it offers to explore new techniques of interaction, which are not possible in our daily activity. Different approaches have been followed to design navigation, selection and manipulation techniques that break the physical laws of the real world allowing end users to perform various tasks. As a step forward, a new method consists of using participants' brain activity and electroencephalographic responses (EEG) to perform new actions within the environment. Brain-Computer Interfaces convert specific brain signals into control commands by recognizing different electrical patterns. Initially, these interfaces have been conceived to extend interaction capabilities of severely disabled people. Nevertheless, in the last decade there have been several attempts to incorporate it as alternative interaction mechanism in applications for all kinds of users [5].

There is a limited number of paradigms used for BCI systems [4]: induced changes of oscillatory activity, P300 evoked potentials and Steady-State Visual Evoked Potentials. BCI systems based on induced oscillations use mostly motor imagery strategies to generate event-related de/synchronization [5].

Motor imagery is one of the first techniques used to allowing people to perform a task by thinking of particular motor actions. Authors in[14] made the first attempt of using motor imagery as a navigation technique within a virtual environment (VE). Performance of motor imagery in VR systems have been evaluated using a first person game based on VR [18] and in an immersive VR Cave-like system for a walking task [16]. The sense of presence elicited in an immersive environment has also being evaluated in these systems for a walking task, highlighting the difficulty of making these systems adequate in terms of overall participants' experience [8]. A BCI based on motor imagery has usually between two and four degrees of freedom. Its main drawback is the necessity of long training periods, which can be made less tiring by the use of VR [17].

Interfaces using P300 are based on a peak in a specific brain activity that appears after an occurrence of a rare and awaited stimulus (Edlinger et al., 2009). These systems allow the discrimination of multiple targets ([22] reported up to 72) and have been successfully used as spelling devices and for VR navigation [10].

SSVEP paradigm occurs when a person focuses[1] on a visual stimulus flickering at a constant frequency. A pattern oscillating at identical frequency can then be observed in the subject's EEG signals[3]. High transfer rates and low training periods of SSVEP-based BCIs make this option as one of the most feasible ones to be used within a VE. Furthermore, this technique is less demanding than other BCI approaches in terms of attentional resources, as the brain response is subconscious. Trejo, Rospital and Matthews (2006) [23] have proven that a simple concentration on the target induces the brain response. Therefore, users can perform additional tasks within the environment. Performance rates perceived by users of BCIs can be improved by providing a visual feedback about the brain activity. Indeed, in different examples of BCI based on motor imagery [24], it is common to include such feedback. Naturalness of the interface is one of the main factors that contribute to improve presence [26].

However, little attention has been paid to make the BCI controller part of the virtual scene. Until now, applications using computer screens for SSVEP stimulation presented the stimuli as static simple objects, such as squares[27].

The objective of this work is to study and improve the usability of SSVEP-based BCIs in VEs. Our main contribution is the use of stimulation targets, which are not only moving, but are also animated and integrated as parts of the virtual world. We expect to use such stimuli in an SSVEP interface, while maintaining user's performance over certain thresholds. Moreover, we also provide feedback to users, giving them information about their mental state in addition to the feedback already provided by their point of view movement within the virtual scene. Feedback about mental activity has indeed already been provided for BCI based on motor imagery, but it has never been studied with SSVEP.

This paper is organized as follows. First, we present the related work in Section 2. Our novel approach for integrating feedback and SSVEP stimuli in virtual worlds is presented in Section 3. In Section 4, we describe the evaluation of this approach through the experimental protocol followed and the results obtained. Finally, the main contributions of this study are discussed within the frame of previous work and the conclusions outlined are presented in Sections 5 and 6, respectively.

2 Related work

SSVEP is a largely studied paradigm for BCIs. Thus, there are several contributions within this research field about the underlying signal processing and its use in VEs. Herrmann (2001) [11] has evaluated various stimulation frequencies that can be used for SSVEP. This study has lead to the conclusion that flickering at frequencies higher than 6 Hz and up to 100 Hz are capable of generating a brain response. Zhu et al. (2009)[27] conducted a thorough study, regrouping 49 research papers concerning SSVEP, and several aspects thereof, such as the hardware used, nature of the stimulation and used frequencies were evaluated. According to this review, most of the SSVEP-based BCIs use lower frequencies (from 12 to 25 Hz) because they produce stronger response[11]. However, visual stimulation in this band can occasionally cause seizures to people suffering from photosensitive epilepsy[7]. As a step forward, Garcia (2008) [9] has investigated the feasibility of SSVEP interfaces using higher frequencies (over 40 Hz), which are unnoticeable to the human eye. The result of the study was that high frequencies are utilizable, however their detection is more difficult compared to lower frequencies.

The number of commands that a standard SSVEP-based BCI can provide is equal to the number of stimulated frequencies that the program can distinguish. Trejo et al. (2006)[23] have used a stimulator using LEDs as flickering targets with a value of 0.5 Hz as the lower difference between stimulated frequencies. In terms of hardware, according to Zhu et al. (2006)[27], flickering stimuli generated with LEDs yielded better results than those obtained with a standard computer screen. Moreover, one can control the flickering frequency of each LED independently, making it possible to generate virtually any stimulation pattern. In contrast, the stimulation frequencies that a computer screen can provide depend on its refresh rate, which largely limits the number of frequencies it can reproduce. In this regard, two studies in particular have focused on increasing the number of commands by using a limited number of frequencies. Shyu, Lee, Liu, and Sie (2010) [20] evaluated combinations of several frequencies for each of the commands with LEDs, creating six commands with four frequencies. Another approach consists in using targets flickering on the same frequency but at a different phase, for instance Jia, Gao, Hong, and Gao (2010) [12] managed to create an interface with 15 commands using a 60 Hz LCD screen.

BCI intends to be a universal tool that can be used for everybody. However, this is not yet the case and it is commonly said that a small portion of population is "BCI illiterate"[2]. Recently, Volosyak, Guger, and Gräser (2010)[25] reported their attempt to design an expert system, referred to by them as a BCI wizard, for choosing the best configuration of different BCI systems. In a preliminary study made to compare P300 and SVEEP systems, they concluded that all the participants could use the P300 interface while 71% (10 out of 14) were successful with an SSVEP interface. Surprisingly, nearly all the participants (9 out of 10) that could properly used both systems preferred the SSVEP system due to the existence of a better feedback and because of its higher information transfer rate (24.8 bits per minute (bpm) against 9.0 bpm). Although this experiment was made with a 2D interface, it reports that SSVEP is suitable for a complex task that requires a high information transfer rate. It also stated that there remains the need for further research concerning the feedback provided to indicate the activation of a control.

Previous research has evaluated the usability of BCIs relying on visual stimulation as controllers in VEs. Martinez, Bakardjian, and Cichocki (2007)[15] have successfully used SSVEP-based BCI to control the movements of a virtual car in four directions on a scene seen from a top-down view. Attending to a 3D environment, a first person game has been used to evaluate performance of a BCI based on motor

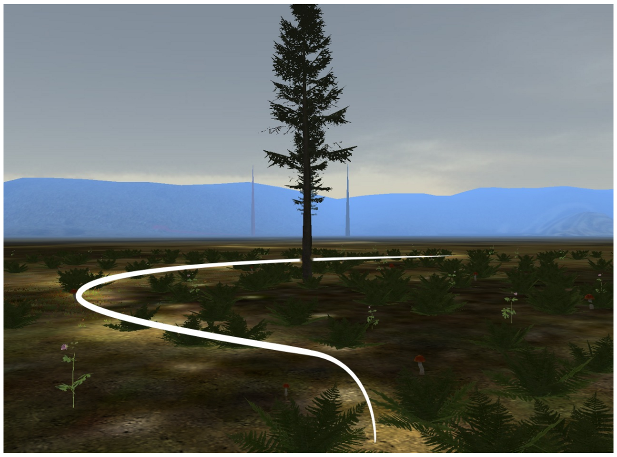


Figure 1: Virtual environment used in the experiment, white line highlights the beginning of the path to follow

imagery[18]. Recently, Donnerer and Steed (2010)[4] used a P300-based BCI in a fully immersive CAVE environment and compared it to non-immersive approach. The system used two types of 3D objects as stimulation targets in the CAVE setup: a grid of 3D cubes and a group of randomly placed objects of various shapes and sizes. One additional paradigm was proposed to the users testing the 2D interface: a simple grid of tiles. Their conclusion was that it is indeed possible to use P300 in a fully immersive environment and that the size of the flashing objects is not important. They stated, however, that in heavily cluttered areas the system might yield an increased number of false detections. Groenegress et al. (2010)[10] have evaluated the feeling of presence in a VE, comparing a P300-based BCI to a gaze-based selection method. Their results have shown that the use of a BCI is detrimental for this factor. However, in their experimental protocol the screen showing BCI controls was placed on the users' side, thus they had to turn their head in order to perform any action.

Lalor et al. (2005)[13] were the first to evaluate the feasibility of using SSVEP to interact with a game in a VE. Furthermore, Faller, Müller-Putz, Schmalstieg, and Pfurtscheller (2010)[6], in a study similar to ours, evaluated the use of SSVEP paradigm within a VE for 3D navigation. In their application, an avatar seen from a third person's view was controlled by three flickering (black/red) 2D squares displayed on a screen. Three commands were available: a step forward, a 45º left turn and a 45º right turn. To validate a command, 1.5 s of signal was required, after which a break time of 4 s was necessary.

Thus, the theoretical rate was 10.9 commands per minute. In their experimental protocol, participants had to perform two tasks: a slalom course around a series of poles and an "apartment" scenario where the user had to go from the starting point to a predetermined point in a complex 3D scene. Such previous research has shown that it is possible to rely on a BCI to navigate in VEs. However, in all previous studies, the visual stimuli are abstract and do not fit into the scene. Our goal is thus to propose a new and more engaging controller for using the SSVEP paradigm based on integrated stimuli and real-time feedback of mental activity.

3 A novel approach for SSVEP-based control in VR: integrated stimulation and real-time feedback

Our novel paradigm introduces two main contributions in the field of SSVEP-based BCI in VEs. Firstly, we propose the integration of the flashing stimuli necessary to elicit SSVEP in brain activity directly as part of the virtual objects, that is to say, within the context of the VE (mimesis and integrated stimulation). Second, we propose to incorporate a real-time visual feedback of detected mental activity into the virtual scene. Both components are expected to improve the usability of SSVEP-based control in virtual worlds.

To illustrate our approach, we target navigation in VEs using SSVEP and Brain-Computer Interfaces. We study navigation in an outdoor environment. In particular, a VE based on a forest has been chosen to conduct the experiments. As illustrated on Figure 1, the scene contained five aligned trees representing a slalom course with two spikes at the end of the path (finish line). The distance between the starting point and the first tree and between the trees was 100 units long. The distance between the last tree and the finish line was 50 units. The point of view was placed 10 units above the ground. The trees were not solid obstacles and the user could pass through them in the case the slalom task was mistaken. In the remainder of this section, we will detail the design of two different types of SSVEP controller, each of them with and without real-time visual feedback of the mental activity. The first controller is a state-of-the-art interface made of flashing arrows and already used in the literature[6]. The second controller is a novel scheme made of virtual objects directly integrated in the virtual scene.

3.1 Introducing integrated stimulation for SSVEP-based BCI

Our novel controller consists of using animated 3D objects as SSVEP controls directly integrated with the environment context. We will refer to this approach as the **Mimesis** interface.

According to Faller et al. (2010)[6], the vertical movement of the flashing objects does not affect the performance of SSVEP interfaces. Based on this finding, we take a further step of animating the targets as well.

We compare the Mimesis interface to a controller based on the current state of the art, referred to as **Overlay** interface. This interface consists of a group of 2D objects drawn on the screen and is similar to other classical SSVEP interfaces[6]. In this case, there was no mimesis of the controls with the forest.

Figure 2 illustrates the Mimesis interface. The users had to focus on one of the three animated flickering butterflies on the screen to move within the VE. The position of the butterfly (front, left or right) determined the direction of their movement (*straight forward* for the front butterfly, *right and forward* for the right butterfly, and *left and forward* for the left butterfly). Rather than to the reference system of the environment, the horizontal positions of the three butterflies were tied to the users' point of view in order to keep them always within the users' field of

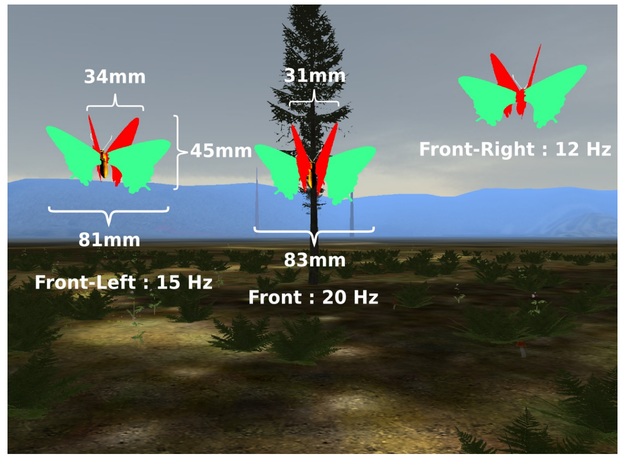


Figure 2: Virtual environment with the Mimesis controller: butterflies were used as more natural and ecological - better integrated in the scene, two frames of butterfly animation are overlapped to illustrate the changing size.

Figure 3: Animation of the butterflies' wings

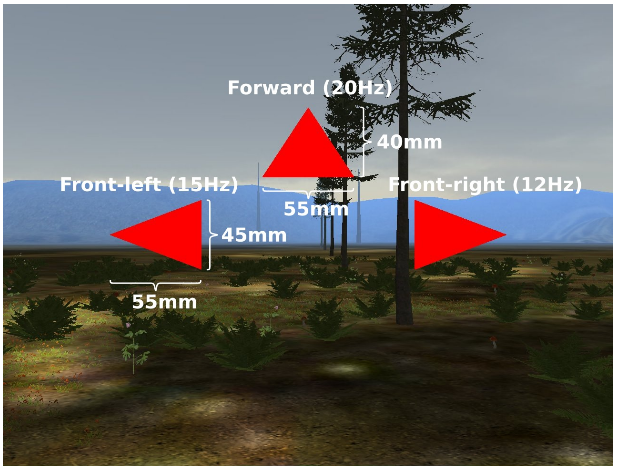
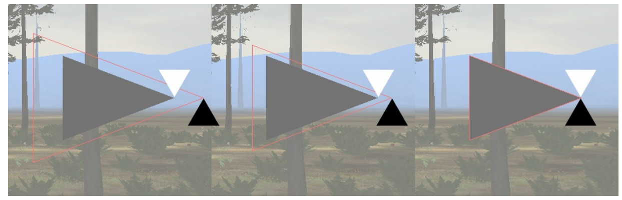
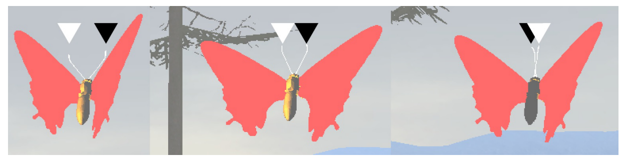


Figure 4: Virtual environment with 2D overlay controller using directional arrows



(a) Evolution of feedback in the Overlay Interface



(b) Evolution of feedback in the Mimesis Interface

Figure 5: Evolution of the feedback from 0 (no concentration) to 1 (command activated). The value of feedback is highlighted in the screenshots by black and white arrows - the greater the distance, the lesser the value

view. With the purpose of making the butterflies more realistic, they were also moved vertically with a random position. This vertical movement was desynchronized among butterflies.

Moreover, these butterflies were animated by flapping their wings (in a desynchronized way for the different butterflies) simulating their typical appearance while flying, albeit slowed down. This animation is illustrated in Figure 3. Furthermore, the flickering at the three frequencies: 12 Hz, 15 Hz and 20 Hz was included by changing the wings' color (red and black) of the right, left and top butterfly, respectively.

As shown in Figure 4, the Overlay interface consisted of three red arrows displayed in the middle of the screen, corresponding to three principal directions - forward, left and right. This controller had a fixed position relative to the screen, independent of the point of view. These three arrows were constantly flickering at three different frequencies (right arrow: 12 Hz, left arrow: 15 Hz and top arrow: 20 Hz), by changing the color of the arrows from red to black and vice versa. Activation of these arrows is directly associated to the users' movement within the environment: e.g., *straight forward* for the up arrow, *right and forward* for the right arrow and *left and forward* for the left arrow. The user's movements were processed identically by the system with both controllers (Overlay/Mimesis), depending on the selected target (arrow/butterfly). Thus, the speed of the forward movement was 12 units/second. The turning occurred at 16.2 deg/s accompanied by a forward movement at the speed of 6.2 units/second. At full forward speed (without slaloming), a user would finish the course in about 46 s.

3.2 Introducing real-time visual feedback of brain activity for SSVEP-based BCI

We propose a novel real-time visual feedback of users' brain activity, directly embedded within the SSVEP controller. The integration of this feedback must be adapted to the controller features. Thus, each controller implementation has a different way to depict the mental state of the user. This additional feedback is expected to improve the controller usability and to reduce the possible users' frustration by increasing the perceived system responsiveness. The assumption of these benefits is notably based on the study of Groenegress et al. (2010)[10], who stated that a mode of interaction where "only thoughts" are used might appear too vague in many aspects and perhaps even bizarre to experienced and frequent users of computers or VEs. The feedback was thus presented to the user differently, depending on the controller used. In the case of the classical Overlay interface, the feedback of the user's brain activity was depicted in the controller as a red triangle placed around each of the three control arrows, as can be seen in Figure 5a. The area of these triangles depended on the feedback value, which was mapped in such a way that the area of the feedback triangle was coincident with the control arrow when the classifier indicated zero distance to the decision hyperplane. After 0.5 s of that instant, the participants' movement direction was updated with the target direction.

Within the 3D interface, a different metaphor of the feedback was used. In this case, the brain activity features were mapped to the movement of the butterflies' antennas. The antennas were rotated in such a way that they were more separated when the subject was not concentrated and crossed when the classifier had validated the command. The concept remained the same – objects becoming closer together represented the "focus" of the user. This feedback is illustrated in Figure 5b.

3.3 Apparatus

EEG signals were recorded using a g.Tec g.USBamp biosignal amplifier[1]. Six active electrodes were used and placed in the occipital area of the subjects' skull at positions CPz, POz, O1, Oz, O2 and Iz according to the international 10/20 system[19]. In addition, a passive reference electrode was placed in the subjects' right ear and a ground electrode (passive) on the AFz position. The signal was recorded at 512 samples per second. All data acquisition and processing was done with the OpenViBE[2] toolset for creating BCI controls. Data from the amplifier was acquired by a dedicated computer running OpenViBE acquisition server. It includes an acquisition server, which is able to interface with several available EEGs – g.USBamp in particular, a scenario designer and a player that allow creation and execution of various signal-processing tasks, respectively.

[1]http://www.gtec.at

[2]http://openvibe.inria.fr

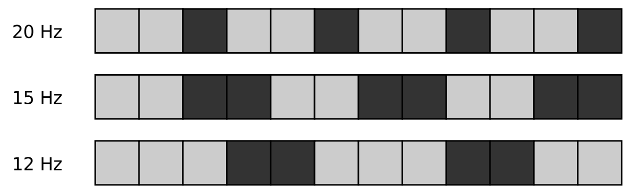


Figure 6: Representation of stimulation frequencies on a 60 Hz computer screen

Other instance of OpenViBE (running the signal-processing program) was launched in another machine, connected to the acquisition server by an Ethernet network. This computer was used to run both, the training and the experimental applications. OpenViBE and the experimental applications communicated using the connection features of VRPN[3].

3.4 Self-paced high-speed BCI control

A new self-paced BCI has also been conceived with the goal of allowing the users a free control of their positions. The controller provides a continuous movement as long as users keep their attention on a specific target. This approach is different from Faller et al.„ (2010)[6] and P300-based navigation systems where the user moves by large steps and turns in fixed angles.

3.4.1 Command extraction

The BCI applied in this study is based on 3-classes, which means that users are able to use three different commands: forward, left turn and right turn. Each of these commands is associated with a target, flickering at 20, 15 and 12 Hz, respectively. Flickering is achieved by switching the color of the targets from red to black, as shown in Figure 6. As an example, 20 Hz corresponds to alternation of two successive red frames and one black frame. Three LDA classifiers are used to detect the presence of increased brain activity, one for each of the stimulated frequencies. Vectors containing two feature values associated

[3]http://www.cs.unc.edu/Research/vrpn/

with two characteristics calculated from the six channels of the recorded signal are supplied to the classifiers. Considering the international 10/20 standard for EEG electrode positions (AES, 1991)[19], the first characteristic is $4 \times Oz - (POz + Iz + O1 + O2)$, which corresponds to a radial current on Oz. The second one is CPz-POz, a tangential current between CPz and POz. These two characteristics were chosen from previous tests made with different combinations, because they provided good performance.

Once the characteristics are calculated, a narrow frequency band (0.75 Hz centered at the stimulated frequency), corresponding to the target flickering frequency, is selected by a band-pass filter (4th –order Butterworth). Afterwards, the average of the signal amplitude in a 500 ms moving window is used as a feature value for the classifier. This window is moved in 100 ms steps. Thus with a 100% performance of the system, users could send 10 commands per second. Once each classifier provides a result, indicating whether a frequency was stimulated or not, the three values are combined. If only one frequency – only one command was allowed at a time – is consecutively stimulated five times, the corresponding command is sent to the application with a delay of 500 ms.

The classifiers were trained with the data obtained after an 8-minute training session (it is 778 and eight times. Thus, each featured vector was extracted and associated with known classes. These vectors were then used for a supervised training of the LDA classifiers.

3.4.2 Feedback calculation

The classifiers described in Section 3.4.1 are used to incorporate the real-time feedback within the controllers. As each feature vector has two values, it can be represented as a point within a plane. As illustrated in Figure 7, the decision hyperplane splits this plane into two halves associated with the two possible decision values - target activation and non-activation. The value of the feedback computed was equal to the distance of the currently evaluated feature vector to this hyperplane. A null or negative value for the normal distance meant that the current feature vector was being evaluated as an accepted stimulation by the classifier. A positive distance meant that the vector belonged to the rejected stimulation class. The distance was normalized by its maximal value in order to obtain a measure between 0 and 1. Our controller is then capable of providing the user with a high-speed brain-based control of his/her movement in the VE. Stimulations integrated into the scene made the controller less intrusive, which in turn should improve the sense of presence. Finally, the provided feedback should increase the perceived responsiveness.

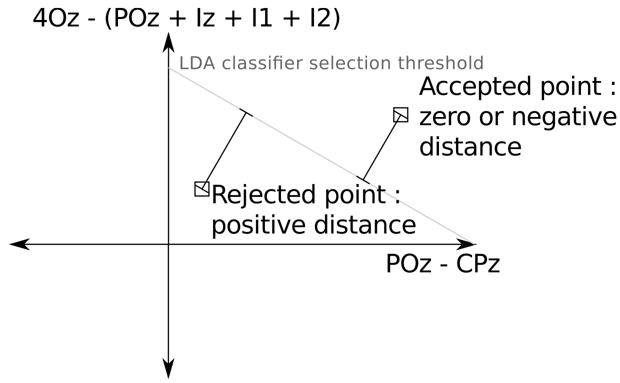


Figure 7: Calculation of feedback value as the distance of a feature vector from the classification hyperplane

4 Experimental evaluation

An experiment has been conducted to evaluate our new controller scheme for SSVEP, using both performance and subjective preference criteria. Other important human factors typically used to validate the interaction in HCI, such as the elicited sense of presence within a VE were also considered. In particular, our new controller scheme (Mimesis interface) was compared to a standard SSVEP controller (Overlay interface), in different configurations (both with and without feedback). Moreover, for the first time, we quantitatively compared an SSVEP interface to a standard input device, referred to as computer keyboard.

The main hypothesis is that using a moving and animated target for SSVEP should improve the feeling of presence reached with an overlay controller while the performances of the BCI would remain unaffected. Providing visual feedback should increase the perceived responsiveness of the system and thus the users' preferences. In comparison with a keyboard, the proposed controller should have largely inferior performance than the keyboard controller. The SSVEP controller was also mainly intended to increase user's preference in detriment of performance.

Figure 8: Participant wearing the EEG cap during one of the BCI trials

4.1 Participants

The experiment was performed with seventeen participants - fourteen men and three women. They volunteered to participate during two sessions of around one hour each. Participants were aged from 21 to 35 (μ= 25.5; σ= 4.3) and all had normal or corrected-to-normal vision. All the participants had previous experience with VR applications but only four of them reported previous experience with BCI.

4.2 Design

The task that participants were asked to perform within the VE consisted of navigating around five trees, which were aligned forming a slalom course, and crossing the finish line at the end. An ideal path was displayed on the floor of the VE using a lighter grass texture to give participants a reference throughout their navigation.

The experiment had a 2 x 2 design with the BCI controller (Overlay or Mimesis) and the condition of feedback (with or without) as the two within-subjects independent variables. The interaction with BCI was performed with the four possible configurations described in Section 4 as a combination of these two factors. The four experimental conditions tested are referred to as: Overlay without Feedback (OV_NFB), Overlay with Feedback (OV_FB), Mimesis without Feedback (MI_NFB) and Mimesis with Feedback (MI_FB). All of the participants were also asked to perform the same navigation task using a keyboard (KB). All participants interacted twice in these five conditions with the keyboard being always used first. To avoid the effect of the order and any possible learning, the order of the BCI conditions were randomized.

The dependent variables considered were task performance, complexity, system responsiveness, comfort and presence. Task performance was computed with three measurements: the feasibility of finishing the task, the time to finish it (Time) and the accuracy (measured as the number of trees they missed throughout the slalom course). All the other variables were processed with the questions shown in Appendix I and with answers anchored in a seven-point Likert scale. Presence was measured via four items extracted from the SUS questionnaire[21] and the answers were operationalised considering the number of questions rated over five. This is the method proposed by Slater et al. (1998)[21] and is referred to from now on as SUS factor.

4.3 Procedure

All participants performed two sessions of approximately one hour and throughout two different days. Experiments were held in an office with closed shutters and with lights turned off. A photo of a participant during the experiment can be seen in Figure 8. Upon arrival to the office, they were informed about their participation as subjects of an experiment made to analyze different factors during their interaction with a VE by using a BCI. Then, they completed a consent form and answered some demographic questions.

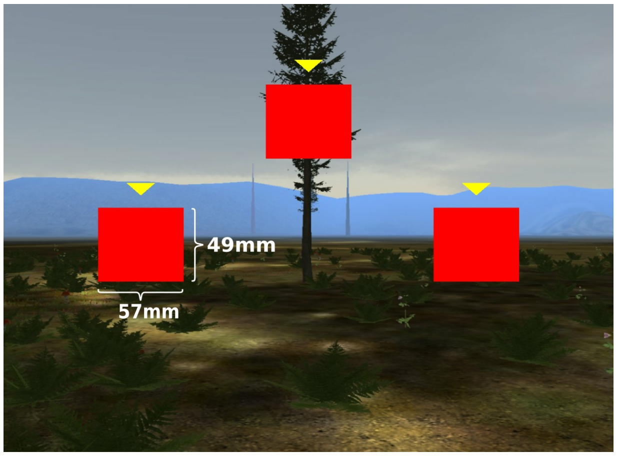


Figure 9: The training scenario showing three square targets on a static background

While the electrodes were being placed on their head, participants were informed that they had to train with a SSVEP interface for around eight minutes. This training procedure consisted of showing to the participants a screen with three flickering targets, at frequencies 20 Hz, 15 Hz and 12 Hz and asking them to direct their gaze to one of them at a time. Participants were sat in front of a monitor at a 60-cm distance.

Two states were alternated during this training. In one state, all of the targets were flickering at their assigned frequencies. During this state, an arrow could mark one of the targets (See Figure 9). When the arrow was present, participants were supposed to look at the target underneath; otherwise, they were asked to direct their gaze to the middle of the screen. The other was a resting state in which all the targets were black.

After the classifier training was conducted, participants were informed that the main goal was to complete the slalom course as fast as they could, in each of the trials that they had to complete. They were informed that trials that would take more than 8 minutes would be considered as a failure, but they were allowed to continue the experiment. The virtual forest was always displayed on a Dell 19" flat screen with 60 Hz refresh rate. The task finished once they crossed the finish line.

	20Hz	**15Hz**	**12Hz**
Performance	90.7 (7.0)	94.4 (4.0)	91.0 (7.0)

Table 1: Average performances (with standard deviation) of the three individual classifiers for the 15 participants that could interact properly

In order to allow participants to get used to the different conditions of the BCI, the first session was devoted solely to training. Thus, during this first session, they were not asked to fill any questionnaire, they could talk throughout the trial and their performance was not taken into consideration in the experiment results. During the second session (held on day two), after all the equipment was in place, participants performed another training session lasting eight minutes to recalibrate the classifier. Next, they were informed that they had to perform five trials in the same conditions as the previous day but with a different order for the BCI trials and without any communication during the task. After each trial, they answered a questionnaire.

4.4 Results

The experiment results were analyzed separately considering first differences among BCI trials and second, comparisons between obtained results in the BCI trials and the Keyboard trial. The results of only fifteen from the seventeen participants were considered. Two of them had to be discarded, as the experiment had not been successfully completed. Due to the unadapted EEG cap, there was not physical contact with the back electrodes (CPz and Oz) for one of the participants and the bad acquisition of the electrical signal hindered the system performance. We could not solve this issue during either of the two sessions. For the second participant removed from the results, it was difficult to activate the target corresponding to the right movement and he was then only able to navigate in front and left directions, making turning right extremely difficult. Table 1 shows the individual classifiers' performances (for each frequency) according to a 10-fold cross-validation test. It is important to note that these performances do not accurately reflect the ability of the subject to move within the virtual scene. This is because, due to their nature, targets within the stimulation were of different shape than the targets used for training. In addition, a combined result of the three classifiers was used to activate a command.

4.4.1 Differences among conditions of the SSVEP controller

Twelve of the fifteen participants (80%) were able to reach the finish line in all conditions, although only nine of them (60%) did it in less than 8 minutes. Three participants finished one condition between 8 and 12 minutes (Participant 1: OV_NFB= 545 s; Participant 13: MI_FB= 568 s and Participant 15: MI_NFB= 694 s). Three participants were not able to finish some of the four trials (Participant 2: MI_NFB and MI_FB; Participant 8: MI_FB; Participant 9: MI_NFB) in a reasonable time, and as they were feeling tired we stopped the application before they have reached the finish line, although they were doing the slalom properly without missing any trees.

Regarding the accuracy of the slalom task, six out of the fifteen participants (40%) failed to go around some trees. Note that we did not consider as a fail those trees not reached because the participants did not finish the task. The percentage of participants that missed some trees in the different interaction conditions were: 20% (3 participants) for OV_NFB and MI_FB, 13% (2 participants) for MI_NFB and 6.6% (1 participant) for OV_FB. These results indicate that participants performed the slalom task more accurately with the overlay controller and when feedback was provided.

Average values of time to finish the task of the twelve participants that finished successfully the five experimental conditions are listed in Table 2. Participants were faster on average completing the slalom in trial OV_NFB (M= 230 s, SD= 120 s), but with a very close value to that obtained in trial OV_FB. Indeed, no significant difference (paired T-tests) was found between these conditions.

A two-factor ANOVA with the two within-subjects variables (Control and Feedback) was performed with time results obtained for participants that finished the four trials (12 participants). This analysis indicated that participants interacted significantly faster with the overlay controller than with the mimesis controller ($F(1,11)= 7.57$, $p= .01$), while not a significant influence ($F(1,11)=0.56$, $p= .46$) was found for the feedback factor.

These time results indicate that a SSEVP controller based on 3D objects diminishes the performance compared to a typical Overlay interface. A nearly significant interaction was also found between control and feedback factors ($F(1,11)= 3.12$, $p= .10$), due to the fact that the feedback had a positive influence in time just for conditions with the mimesis controller. Indeed, the time difference between MI_NFB and MI_FB conditions assessed with a Student's t-test was nearly significant ($t11=1.75$; $p= .13$).A two-factor ANOVA was also performed with questionnaire results obtained for the different conditions of the SSVEP controller (OV_FB, OV_NFB, MI_NFB, MI_FB) and considering data of the fifteen participants. Table 3 lists the influence (significance values) of these two factors in each condition (average and standard deviation) for Difficulty, Responsiveness (Response), Comfort and Presence. For Presence, results are shown for each question (P1, P2, P3, P4) separately and for the SUS factor. On average, questionnaire results in all of the BCI conditions indicated that the interaction was difficult for participants, which, in comparison to standard input methods, is understandable. As shown in Table 3, the most difficult condition was MI_NFB (M= 3.1, SD= 1.5). Furthermore, a significant influence of the control factor ($F(1,14)= 8.2$, $p= .01$) indicated that the interaction by using 3D animated and moving objects was perceived significantly more complex, and that the feedback provided was not perceived as a considerable help for any of the controllers ($F(1,14)= 0.08$, $p= .77$).

Responsiveness was rated higher for condition OV_FB (M= 5.0, SD= 0.8). In this case, the ANOVA performed also indicated that the control feedback provided was beneficial for the perceived responsiveness ($F(1,14)= 6.0$; $p= .02$) and that the

	OV_NFB	OV_FB	MI_NFB	MI_FB	KB
M(SD)	230 (120)	242 (129)	387 (153)	337 (153)	56 (5)

Table 2: Average values of time to finish measurement (s) and standard deviation for the 12 participants that finished all the trials

	OV_NFB	OV_FB	MI_NFB	MI_FB	Cont	Feed	KB
Difficulty	4.5 (1.4)	4.4 (1.1)	3.1 (1.5)	3.4 (1.4)	.01	.77	6.4 (0.9)
Response	4.8 (1.2)	5.0 (0.8)	3.8 (1.3)	4.5 (1.2)	.02	.10	6.2 (0.9)
Comfort	4.4 (1.2)	4.4 (1.0)	4.3 (1.2)	4.4 (0.9)	.86	.90	1.7 (1.0)
P1	3.6 (2.0)	3.7 (2.1)	4.1 (2.0)	4.2 (2.1)	.08	.43	4.2 (2.0)
P2	2.4 (1.3)	2.4 (1.5)	2.3 (1.4)	2.4 (1.5)	.67	.75	2.4 (1.5)
P3	4.0 (1.8)	4.1 (1.8)	3.8 (1.5)	4.1 (1.8)	.49	.30	4.5 (1.8)
P4	3.2 (1.6)	3.0 (1.4)	3.0 (1.3)	3.5 (1.6)	.16	.33	3.8 (1.6)
SUS	0.6 (0.8)	0.6 (0.8)	0.4 (0.7)	1.0 (1.0)	.43	.11	0.9 (1.0)

Table 3: Average (M, SD) values of self-reported measurements and influence of independent (p) variables (control and feedback) for the 15 participants that could interact properly

feedback provided seemed to improve this perception with a nearly significant influence (F(1,14)=3.0, p= .10). As for the comfort measurement, no significant influence was found for any of the two factors. Comfort was rated with nearly the same value in the four BCI conditions.

As can be also seen in Table 3, no influence of the feedback condition was found in presence questions analyzed separately. However, its influence was more evident although without a significant influence in the SUS factor (F(1,14)=2.74, p= .11), indicating higher level of presence when feedback was provided. This analysis also indicated a significant interaction between control and feedback factors (F(1,14)= 4.35, p= .05), because the positive influence of the feedback in presence was evident for the Mimesis condition while no effect was found for the Overlay condition. Indeed, presence was significantly higher in MI_FB than in MI_NFB (T-test: t14= 2.25, p= .04), indicating that the sense of presence was higher when information about their brain activity was supplied by the Mimesis controller. As for the control factor, according to the first question, participants felt more "like in a virtual forest" while using the Mimesis interface with a nearly significant difference (F(1,14)= 3.5, p= .08). MI_FB (M=1.0, SD=1.0) was the best condition considering the factor SUS (note that this value refers to the number of answers rated over 5). Indeed, a paired T-test performed with presence results indicated that the sense of presence in MI_FB condition was significantly or nearly significantly higher than in the other conditions (MI_FB-OV_NFB: t14= 1.7, p= .09; MI_FB-OV_FB: t14= 2.0, p= .05; MI_FB-MI_NFB: t14= 2.2, p= .04). However, no significant influence was found for the control factor.

4.4.2 SSVEP controller vs. Keyboard

Results of the keyboard trial were compared with those obtained for the BCI conditions. As expected, when participating in the keyboard trial all the par-

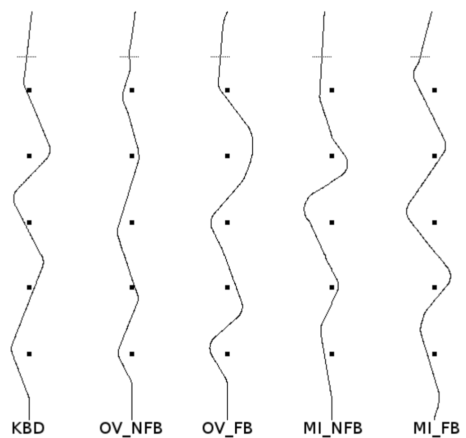


Figure 10: Examples of paths followed by subject 12 during the navigation task. Squares represent the trees, the start line is on the left and a dotted line on the right marks the end.

ticipants finished the slalom task without missing any of the trees. Moreover, the time to finish was significantly faster (at the level of .001) within the keyboard condition (M= 56 s, SD= 5 s). Thus, results in the BCI conditions were between 3.9 (OV_NFB) and 6.8 (MI_NFB) times slower than those obtained in the keyboard condition. The paths followed for participant 12 in the five experimental conditions are shown in Figure 10.

Attending to subjective reports, less difficulty (M=6.4, SD=0.9) and a higher responsiveness (M=6.2, SD= 0.9) were also reported for the keyboard condition with a significant difference with values reported in the BCI conditions. As expected, the keyboard interaction was also rated more comfortable (M=1.7, SD= 1.0) with a significant difference. In the keyboard condition, presence results were low (M=0.93, SD=1.03). This low rate was also observed for the BCI interface. This can be due to the use of a low-immersion configuration (desktop VR without stereovision or sound) and also to the simplicity of the environment (just a few trees). The nature of the task they had to perform (slalom between trees) might have had a negative influence on presence factor. The SUS factor reported higher presence for the 3D SSVEP interface with feedback (MI_FB), but without significant difference. Indeed, presence in the keyboard condition was only significantly higher than in the least efficient BCI condition (KB-MI_NFB= 0.46, t14= 2.2, p= .01).

5 Discussion

Our results have highlighted the feasibility of integrating an SSVEP controller directly into the context of a virtual scene. We have observed a decreased performance with flashing stimuli, which were animated and moving. This decrease may be linked to the fact that users attention gets distracted when he has to focus on a moving object, however according to[6] vertical movement of SSVEP targets should not diminish the performance. The main problem is that the animation of the object modifies the flickering surface's size. Since the training was done only once and with static targets, there were moments when the elicited response might have needed a lower threshold of activation.

To the author's best knowledge, this is the first attempt to use a mimesis controller in a SSVEP-based BCI. A similar approach has been followed by Donnerer and Steed (2010)[4], but with a P300 interface. Results of their experiment have also shown the feasibility of using non-regular size objects within the scene. They showed that it is possible to use flashing stimuli in an immersive CAVE interface. Even though P300 is fundamentally different from SSVEP, this possibility could be explored to further increase the sense of presence, which was found low here even for the keyboard controller. Further research is also necessary to evaluate the extent to which controller objects that are integrated too tightly within the scene may pose a problem attending to attention, i.e. by activating a command without a voluntary intention on behalf of the users.

The presence of visual feedback about user's mental activity related to SSVEP was found to have a positive influence on performance in the case of the mimesis controller. The navigation task has indeed been completed faster when the antennas of the butterflies provided information about participants' brain activity. This was not the case for the Overlay controller, condition in which no difference was found in terms on completion time. This difference could indicate that the performance gap between the Mimesis controller and the Overlay controller can be addressed, to some extent, by providing feedback. We can assume that the optimal performance can be obtained by using static 2D targets. Different methods could be explored to attain its level of performance with a visually more complex controller, notably the training method should be adapted to each type of the controller.

Considering results obtained in the other human factors evaluated, the positive effect of the feedback in the system responsiveness and in presence has also indicated that this information has a positive influence in the overall participants' experience, which has previously been stated as one of the main drawback of certain BCI[8]. Indeed, on average, in all the self-reported measurements, the best condition has always provided feedback. As mentioned in Section 3, Groenegress et al. (2010)[10] have stated that one of the main drawbacks of using BCI in which only thoughts are used to interact within a VE may be the lack of physical actions associated with the use of these interactions. Results of the study presented here seem to indicate that the inclusion of movements within the controller, anticipating the corresponding action within the environment may overcome, to some extent, the lack of physical actions. The inclusion of the condition in which participants interacted with a keyboard has also allowed quantifying the extent to which an SSVEP-based BCI may be comparable to a standard input device. As expected, transfer rates have been significantly lower for all of the BCI conditions considered, when they were compared with the keyboard controller. Nevertheless, the average time to finish the slalom was only 4 to 6 times slower in the BCI conditions. However, some participants could finish the task just taking only twice or three times more time than with a keyboard. The fact that these participants achieved 50% of the performance of a keyboard controller is very promising for future usages of BCI and SSVEP in VEs. Furthermore, we did not observe a significant difference in results concerning the elicited sense of presence between the BCI conditions and the keyboard controller. This result is in contrast with the one obtained by Groenegress et al. (2010)[10]. In a similar analysis of presence considering a P300 based BCI and a gaze-based interface for selection, they reported significantly lower scores in the BCI conditions for presence criteria. Thus, the authors concluded: "We conjecture that participants do not gain any useful information about the virtual space and that it cannot be integrated with the P300 interface in a useful way" (p.9).

Taken together, our results suggest that integrating the stimulation and feedback related to SSVEP-based Brain-Computer Interfaces in VEs is a promising approach. In future applications, the flickering stimuli could be included into other and varied objects completely embedded within the scene, such as different natural sources of light. Using such stimulations would require the use of a more elaborate detection method to compensate for the performance decrease.

6 Conclusion

A new approach has been presented for the design of an SSVEP-based BCI controller used to interact within a VE. We have described the use of an ecological controller with the particularity of integrating the stimuli necessary to evoke brain responses into 3D objects of the VE. Furthermore, with the goal of improving participants' perception of the system responsiveness, visual feedback about their brain activity has also been designed and included in the controller. This feedback has also been made part of the 3D object used to provide stimulation and kept within the context of the environment.

These two approaches were successfully implemented in an interface that allows navigation within a virtual outdoor natural scene. As an example of the feasibility of this technique, it was implemented via using animated virtual butterflies flying in front of the user in a natural way, that is to say, without breaking the credibility of that specific environment. With the same aim, the butterflies' antennas were used to display real-time feedback of the detected SSVEP. The evaluation carried out with this controller has shown that such novel scheme for SSVEP-based BCI can be successfully used to control a first-person 3D navigation, providing a complete freedom of movement and a self-paced BCI to the user. Taking the nature of BCI into account, the transfer rate was comparable to the one of a classical controller (keyboard). The signal-processing scheme used in this study yielded good results albeit it was very simple. This study has therefore demonstrated that SSVEP controls could be integrated into the scene as animated and moving objects, but with a tradeoff between performance and subjective preference. Performance in terms of interaction rapidness was negatively impacted and the elicited sense of presence improved when the SSVEP controller was combined with our novel method of providing visual feedback of users' brain activity. Taken together, our results suggest that integrated stimulation and real-time feedback could therefore be further used for SSVEP-based BCI in virtual worlds, mainly on those systems where performance requirements can be relaxed in favor of a more immersive experience.

Acknowledgments

The authors wish to thank Aurélien van Langhenhove and Yann Renard for their help with the application development and EEG signal processing. This work was supported by the French National Research Agency within the OpenViBE2 project and grant ANR-09-CORD-017.

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