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Navigating in Virtual Worlds Using a Self-Paced SSVEP-Based Brain–Computer Interface with Integrated Stimulation and Real-Time Feedback

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 reduced performance in terms of speed. This suggests that SSVEP-based BCI interfaces for virtual environments could move on from static targets and use integrated and animated stimuli presented in an ecological way for controls in systems where performance demands could be relaxed to benefit an improvement in interaction naturalness.

1 Introduction

One of the main advantages of virtual reality (VR) is the opportunity that it offers to explore new techniques of interaction that 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

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method consists of using participants' brain activity and electroencephalographic responses (EEG) to perform new actions within the environment. Brain–computer interfaces (BCIs) 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 an alternative interaction mechanism in applications for all kinds of users (Edlinger, Holzner, Groenegress, Guger, & Slater, 2009; Freeman, Mikulka, Prinzel, & Scerbo, 1999; Mühl et al., 2010; Nijholt, Reuderink, & Oude Bos, 2009).

There are a limited number of paradigms used for BCI systems (Donnerer & Steed, 2010): 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 synchronization and desynchronization (Edlinger et al., 2009).

Motor imagery is one of the first techniques used to allow people to perform a task by thinking of particular motor actions. Leeb et al. (2007) made the first attempt of using motor imagery as a navigation technique within a virtual environment (VE). The performance of motor imagery in VR systems has been evaluated using a first-person game based on VR (Scherer et al., 2007) and in an immersive VR CAVE-like system for a walking task (Pfurtscheller et al., 2006). The sense of presence elicited in an immersive environment has also been evaluated in these systems for a walking task, highlighting the difficulty of making these systems adequate in terms of participants' overall experience (Friedman et al., 2007). A BCI based on motor imagery has usually between two and four degrees of freedom (DOF). Its main drawback is the necessity of long training periods, which can be made less tiring by the use of VR (Ron-Angevin & Díaz-Estrella, 2009).

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 (Takano, Komatsu, Hata, Nakajima, & Kansaku, 2009, reported up to 72) and have been successfully used as spelling devices and for VR navigation (Groenegress, Holtzner, Guger, & Slater, 2010).

SSVEP paradigm occurs when a person focuses (Allison et al., 2007) on a visual stimulus flickering at a constant frequency. A pattern oscillating at an identical frequency can then be observed in the subject's EEG signals (Ding, Sperling, & Srinivasan, 2006). High transfer rates and low training periods of SSVEP-based BCIs make this option 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, Rosipal, and Matthews (2006) 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 visual feedback about brain activity. Indeed, in different examples of BCI based on motor imagery (Velasco-Álvarez, Ron-Angevin, & Blanca-Mena, 2010), it is common to include such feedback. Naturalness of the interface is one of the main factors that contribute to improved presence (Witmer & Singer, 1994). However, little attention has been paid to making 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 (Zhu, Bieger, García-Molina, & Aarts, 2009).

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 the user's performance above 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 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) has evaluated various stimulation frequencies that can be used for SSVEP. This study has led 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) conducted a thorough study, regrouping 49 research papers concerning SSVEP, and several aspects thereof, such as the hardware used, nature of the stimulation and the frequencies used, were evaluated. According to this review, most of the SSVEP-based BCIs use lower frequencies (from 12 to 25 Hz) because they produce a stronger response (Hermann). However, visual stimulation in this band can occasionally cause seizures to people suffering from photosensitive epilepsy (Fisher, Harding, Erba, Barkley, & Wilkins, 2005). As a step forward, Garcia (2008) has investigated the feasibility of SSVEP interfaces using higher frequencies (over 40 Hz), which are not noticeable 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) 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), 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) evaluated combinations of several frequencies for each of the commands with LEDs, creating six commands with four frequencies. Another approach consists of using targets flickering on the same frequency but at a different phase; for instance, Jia, Gao, Hong, and Gao (2010) managed to create an interface with 15 commands using a 60-Hz LCD screen.

BCI is intended 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 (Dickhaus, Sannelli, Müller, Curio, & Blankertz, 2009). Recently, Volosyak, Guger, and Gräser (2010) 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 only 71% (10 out of 14) were successful with an SSVEP interface. Surprisingly, nearly all the participants (9 out of 10) who could properly use both systems preferred the SSVEP system due to the existence of a better feedback and because of its higher information transfer rate (24.8 bpm vs. 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 the need remains 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) 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. In a 3D environment, a first-person game has been used to evaluate the performance of a BCI based on motor imagery (Scherer et al., 2007). Recently, Donnerer and Steed (2010) used a P300-based BCI in a fully immersive CAVE environment and compared it to a nonimmersive 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) evaluated the feeling of presence in a VE, comparing a P300-based BCI to a gaze-based selection method. Their results showed 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) 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), in a study similar to ours, evaluated the use of the SSVEP paradigm within a VE for 3D navigation. In their application, an avatar seen from a third-person point of view was controlled by three flickering (black/red) 2D squares displayed on a screen. Three commands were available: a step forward, a 45° left turn, and a 45° 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. 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.

Figure 1. *Virtual environment used in the experiment. White line highlights the path to follow.*

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 BCIs. We study navigation in an outdoor environment. In particular, a VE based on a forest was chosen to conduct the experiments. As illustrated in 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 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 has already been used in the literature (Faller et al., 2010; Nijholt et al., 2009). 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), 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 the overlay interface. This interface consists of a group of 2D objects drawn on the screen and is similar to other classical SSVEP interfaces (Faller et al., 2010; Nijholt et al., 2009). In this case, there was no mimesis of the controls with the forest.

Figure 2 illustrates the mimesis interface. The users focused 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 being tied 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 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 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.

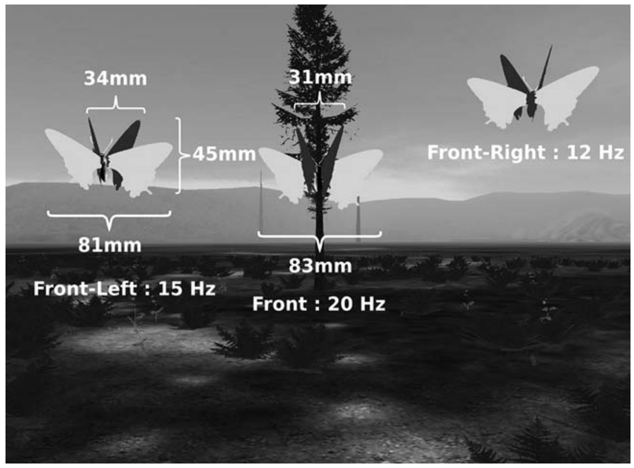

Figure 2. *Virtual environment with the mimesis controller: butterflies were used as more natural and ecological—better integrated in the scene. Two frames of butterfly animation are overlapped to illustrate the changing size.*

Figure 3. *Animation of the butterflies' wings.*

As shown in Figure 4, the overlay interface consisted of three red arrows displayed in the middle of the screen, corresponding to the 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 was directly associated with the users' movement within the environment; for example, straight forward for the up arrow, right and forward for the right arrow, and left and forward for the left arrow.

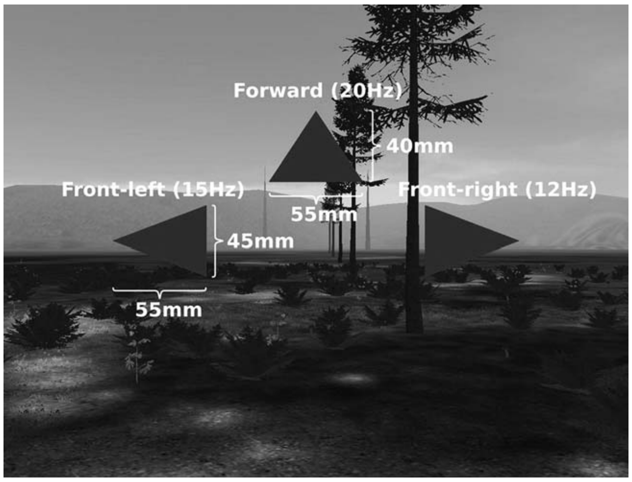

Figure 4. *Virtual environment with 2D overlay controller using directional arrows.*

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/s. The turning occurred at 16.2 deg/s accompanied by a forward movement at the speed of 6.2 units/s. 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), 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 5(a). The area of these triangles depended on the feedback value, which was mapped in such a way that the area of the feedback triangle coincided 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' antennae. The antennae 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 5(b).

3.3 Apparatus

EEG signals were recorded using a g.Tecg.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 (AES, 1991). 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 were acquired by a dedicated computer running the 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.

One other instance of OpenViBE (running the signal-processing program) was launched in another machine,

1. http://www.gtec.at
2. http://openvibe.inria.fr

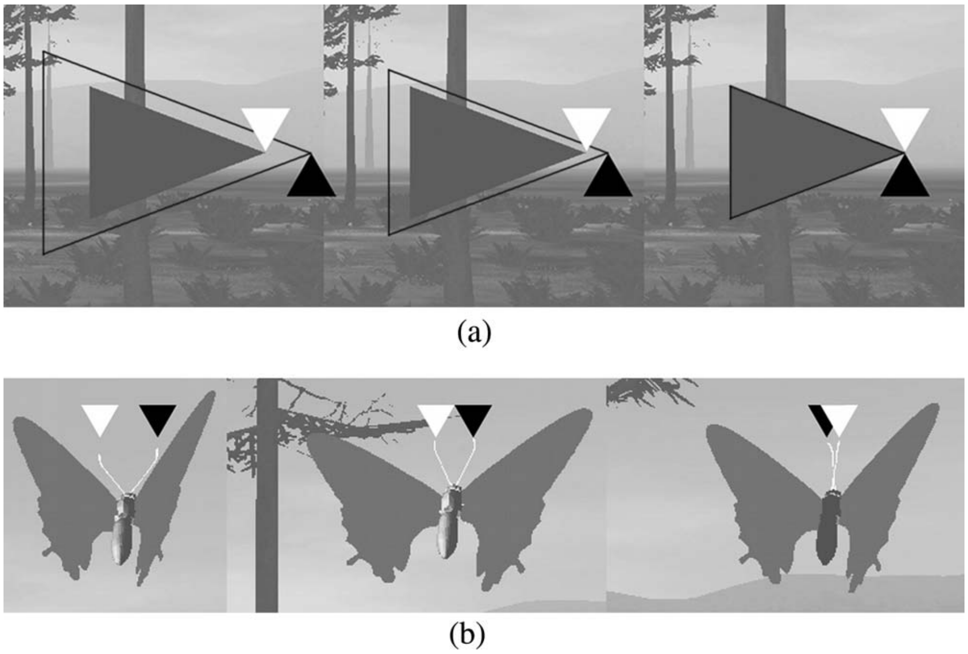

Figure 5. *Evolution of the feedback from 0 (no concentration) to 1 (command activated). The value of feedback is highlighted in the screen shots by black and white arrows: the greater the distance, the lesser the value. (a) Evolution of feedback in the overlay interface. (b) Evolution of feedback in the mimesis interface.*

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 was conceived with the goal of allowing the users free control of their positions. The controller provides for continuous movement as long as users keep their attention on a specific target. This approach differs from Faller et al. (2010) 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 three 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.

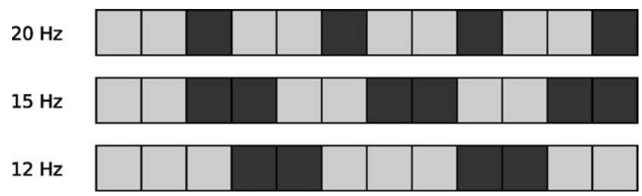

Figure 6. *Representation of stimulation frequencies on a 60-Hz computer screen.*

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 with two characteristics calculated from the six channels of the recorded signal are supplied to the classifiers. Considering the international 10/20 standard for

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

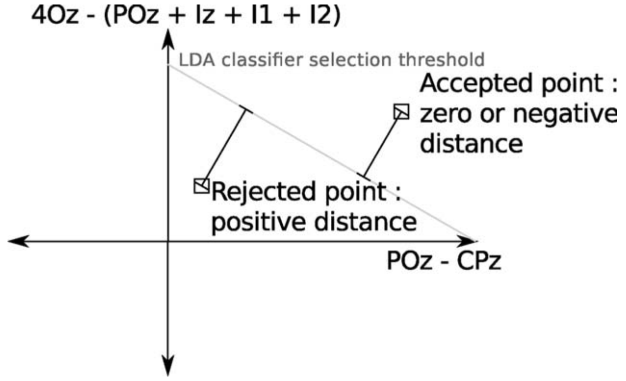

Figure 7. *Calculation of feedback value as the distance of a feature vector from the classification hyperplane.*

EEG electrode positions (AES, 1991), 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 (fourth order Butterworth). Afterward, 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 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-min training session (see Section 4.3). During this training session, each frequency was stimulated during seven seconds 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 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 nonactivation. 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 or 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.

4 Experimental Evaluation

An experiment was 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 performance 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 compared to the keyboard controller. The SSVEP controller was also mainly intended to increase the user's preference, to the detriment of performance.

4.1 Participants

The experiment was performed with seventeen participants, 14 men and three women. They volunteered to participate during two sessions of around 1 hr each. Participants were aged from 21 to 35 ($\mu = 25.5$; $\sigma = 4.3$) 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 2×2 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 always being used first. To avoid the effect of the order and any possible learning, the order of the BCI conditions was randomized.

The dependent variables considered were task performance, complexity, system responsiveness, comfort, and presence. Task performance was computed using 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 1 and with answers anchored in a 7-point Likert scale. Presence was measured via four items extracted from the SUS questionnaire (Slater, Steed, McCarthy, & Maringelli, 1998) and the answers were operationalized considering the number of questions rated over five. This is the method proposed by Slater et al. (1998) and is referred to from now on as SUS factor.

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

4.3 Procedure

All participants performed two sessions of approximately 1 hr over two different days. Experiments were held in an office with closed shutters and with the lights turned off. A photo of a participant during the experiment can be seen in Figure 8. Upon arrival at the office, they were informed about their participation as subjects of an experiment designed 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.

While the electrodes were being placed on their head, participants were informed that they had to train with an SSVEP interface for around 8 min. This training procedure consisted of showing 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

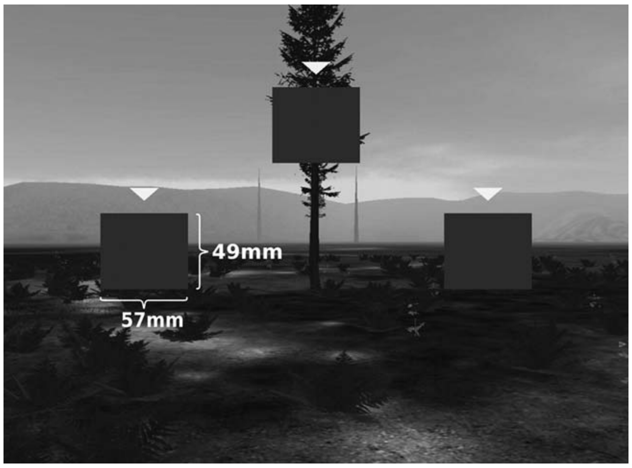

Figure 9. *The training scenario showing three square targets on a static background.*

of them at a time. Participants were seated in front of a monitor at a 60 cm distance.

Two states were alternated during this training. In one state, all of the targets flickered 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 state 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 min 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.

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 out any questionnaires, 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 8 min to recalibrate the classifier.

Table 1. *Average Performances (with SD) of the Three Individual Classifiers for the 15 Participants who Could Interact Properly*

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

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 15 of the 17 participants were considered. Two of them had to be discarded, as the experiment was not successfully completed. Due to a maladapted EEG cap, there was no 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 forward 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 15 participants (80%) were able to reach the finish line in all conditions,

Table 2. *Average Values of Time to Finish Measurement (s) (with SD) for the 12 Participants who Finished All the Trials*

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

although only nine of them (60%) did it in less than 8 min. Three participants finished one condition in between 8–12 min (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 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 15 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 who missed some trees in the different interaction conditions were: 20% (three participants) for OV_NFB and MI_FB, 13% (two participants) for MI_NFB, and 6.6% (one participant) for OV_FB. These results indicate that participants performed the slalom task more accurately with the overlay controller and when feedback was provided.

The average values of time to finish the task of the 12 participants who successfully finished the five experimental conditions are listed in Table 2. The 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 who 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 a nonsignificant 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 the MI_NFB and MI_FB conditions assessed with a Student's t-test was nearly significant, $t_{11} = 1.75$; $p = .13$. 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 from the 15 participants. Table 3 lists the influence (significance values) of these two factors in each condition (average and SD) for Difficulty, Responsiveness (Response), Comfort, and Presence. For Presence, the results are shown for each question (P1, P2, P3, P4) separately and for the SUS factor.

On average, the 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 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

Table 3. *Average M (SD) Values of Self-Reported Measurements and Influence of Independent (p) Variables (Control and Feedback) for the 15 Participants who Could Interact Properly*

	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)

the two factors. Comfort was rated with nearly the same value in the four BCI conditions.

As can also be 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 a higher level of presence when feedback was provided. This analysis also indicated a significant interaction between the control and feedback factors, $F(1, 14) = 4.35$, $p = .05$, because the positive influence of the feedback on 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: $t_{14} = 2.25$, $p = .04$, 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 the MI_FB condition was significantly or nearly significantly higher than in the other conditions, MI_FB-OV_NFB: $t_{14} = 1.7$, $p = .09$; MI_FB-OV_FB: $t_{14} = 2.0$, $p = .05$; MI_FB-MI_NFB: $t_{14} = 2.2$, $p = .04$. However, no significant influence was found for the control factor.

4.4.2 SSVEP Controller versus Keyboard. The results of the keyboard trial were compared with those obtained for the BCI conditions. As expected, when participating in the keyboard trial, all the participants 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, the 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 the 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

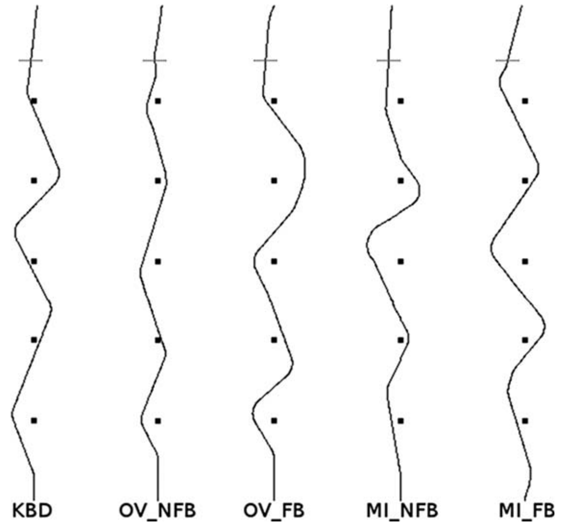

Figure 10. *Examples of paths followed by Subject 12 during the navigation task. Squares represent the trees, the start line is at the bottom of the figure, and a dotted line on the top marks the end.*

only significantly higher than in the least efficient BCI condition, KB – MI_NFB $= 0.46$, $t_{14} = 2.2$, $p = .01$.

5 Discussion

Our results highlighted the feasibility of integrating an SSVEP controller directly into the context of a virtual scene. We observed decreased performance with flashing stimuli, which were animated and moving. This decrease may be linked to the fact that users' attention gets distracted when focusing on a moving object; however, according to Faller et al. (2010), 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 authors' best knowledge, this is the first attempt to use a mimesis controller in a SSVEP-based BCI. A similar approach was followed by Donnerer and Steed (2010), but with a P300 interface. The results of their experiment showed 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 the problem of attending to attention, that is, by activating a command without a voluntary intention on the part of the users.

The presence of visual feedback about the 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 was indeed completed faster when the antennae 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 of 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 optimal performance can be obtained by using static 2D targets. Different methods could be explored to attain the level of performance with a visually more complex controller; notably, the training method should be adapted to each type of controller.

Considering the results obtained for the other human factors evaluated, the positive effect of the feedback in the system responsiveness and in presence also indicated that this information has a positive influence on overall participants' experience, which has previously been stated as one of the main drawbacks of certain BCI (Friedman et al., 2007). 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) 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. The 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 quantification of the extent to which an SSVEP-based BCI may be comparable to a standard input device. As expected, transfer rates were 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 four to six times slower in the BCI conditions. However, some participants could finish the task just taking only two or three times as much time compared to using a keyboard. The fact that these participants achieved 50% of the performance of a keyboard controller is very promising for future uses 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). 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 BCIs 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 was 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 was also designed and included in the controller. This feedback was made part of the 3D object used to provide the 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’ antennae were used to display real-time feedback of the detected SSVEP.

The evaluation carried out with this controller showed that this novel scheme for SSVEP-based BCI can be successfully used to control a first-person 3D navigation, providing 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 a classical controller (keyboard). The signal-processing scheme used in this study yielded good results even though it was very simple.

This study demonstrated that SSVEP controls could be integrated into the scene as animated and moving objects, but with a trade-off between performance and subjective preference. Performance in terms of interaction rapidity 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.

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APPENDIX I. Presence Questionnaire

How difficult was the task of navigating between the trees?

1	2	3	4	5	6	7
Very difficult			*Regular*			*Very easy*

Did the system respond to your actions in a proper way?

1	2	3	4	5	6	7
Never			*Sometimes*			*All the time*

Did you feel comfortable during your interaction within the environment?

1	2	3	4	5	6	7
Very Comfortable			*Normal*			*Very Uncomfortable*

To what extent did you feel like you were in a virtual forest?

1	2	3	4	5	6	7
Not at all			*Sometimes*			*Most of the time*

To what extent were there moments during which you felt the virtual forest was real?

1	2	3	4	5	6	7
Never			*Sometimes*			*Most of the time*

Do you think of the virtual forest as an image you saw or as a place you visited?

1	2	3	4	5	6	7
As an image						*A place*

During the experience did you feel you were in a forest or in a laboratory?

1	2	3	4	5	6	7
In a laboratory						*In a forest*