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Effects of P300-Based BCI Use on Reported Presence in a Virtual Environment

Abstract

Brain–computer interfaces (BCIs) are becoming more and more popular as an input device for virtual worlds and computer games. Depending on their function, a major drawback is the mental workload associated with their use and there is significant effort and training required to effectively control them. In this paper, we present two studies assessing how mental workload of a P300-based BCI affects participants' reported sense of presence in a virtual environment (VE). In the first study, we employ a BCI exploiting the P300 event-related potential (ERP) that allows control of over 200 items in a virtual apartment. In the second study, the BCI is replaced by a gaze-based selection method coupled with wand navigation. In both studies, overall performance is measured and individual presence scores are assessed by means of a short questionnaire. The results suggest that there is no immediate benefit for visualizing events in the VE triggered by the BCI and that no learning about the layout of the virtual space takes place. In order to alleviate this, we propose that future P300-based BCIs in VR are set up so as require users to make some inference about the virtual space so that they become aware of it, which is likely to lead to higher reported presence.

1 Introduction

Noninvasive BCIs offer a flexible method to model numerous different operations and despite their comparatively slow transfer rates they are becoming more and more popular as an input device for virtual reality (VR) for severely disabled as well as healthy people. While much research has been carried out to demonstrate the value of BCIs in rehabilitation, either in conjunction with or without the use of VR technology, the latest generation of BCI systems specifically target the general population. Some off-the-shelf BCIs[1] exist that can, for example, be used as auxiliary controllers for computer games and research has been quick to adapt to the trend exploiting BCIs in educational or entertainment applications (Fairclough, 2008; Nijholt, Tan, Allison, del R. Milan, & Graimann, 2008).

Much work has been carried out exploiting the P300-component and motor imagery for navigation and object manipulation in VR. Thus far, however, no

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[1] For example, by http://emotiv.com/ .

study has addressed the impact of BCI use on presence in virtual environments. In this paper, we present the more specific relationship between the use of a P300-based BCI and presence. We posit that in a P300-controlled environment, mental capacities are directed at the P300 interface and that little or no registration occurs keeping track of events taking place in the VE or the environment itself. We tested this by comparing self-reported presence scores and commentary taken in a BCI-controlled interaction with scores collected in a second study where gaze-based interaction (Pierce et al., 1997; Bowman, Koller, & Hodges, 1997) was used in the same VE.

Previously, we reported on a P300-based BCI for smart home control that used three different conditions varying the number of classifying iterations between eight and two (Edlinger, Holzner, Groenegress, Guger, & Slater, 2009), and where user performance was evaluated as well as self-reported sense of presence. We discovered that average presence scores were much lower than in other environments that do not use the P300-based BCI as a primary interface. This may have been caused solely by the high mental workload that is required to use the BCI. Whatever the cause, it demonstrated that naïve use of P300-based BCIs for interaction in VR potentially undermines the user experience, thus undermining the use of P300-based BCIs and VR for prototyping control of real smart homes, or for applications such as entertainment. In order to compare the self-reported presence results gathered in our first study, we ran a second study where we changed the input device and, instead of using a BCI, we used a gaze-based method combined with wand navigation to let participants control items in the VE.

2 Related Work

Brain recordings have been used in a variety of different contexts, for example, to monitor a person's performance, attention, or fatigue (Huang, Jung, & Makeig, 2007; Cardillo, Russo, LeDuc, & Torch, 2007). While these examples do not technically provide us with a BCI that "reads" thoughts, they show how this technology can be used as a supplementary tool in order to augment human performance in a number of tasks. More sophisticated BCI applications, however, in particular those based on the P300 interface, demonstrate people's ability to control items on a computer screen using thoughts alone (Farwell & Donchin, 1988). The P300 ERP has been exploited extensively as a spelling device (Guan, Thulasidas, & Wu, 2004; Krusienski et al., 2006; Sellers & Kübler, 2006), in which a matrix of alphanumeric letters is presented on a screen and a person can spell words by selecting its letters one by one.

The idea of using a BCI to control a VE is not new, and its efficacy has been demonstrated in different contexts. Bayliss and colleagues introduced a virtual smart home in which users could control five appliances via a P300-controlled BCI (Bayliss, Inverso, & Tentler, 2004; Bayliss, 2003). The work, however, only acted as a proof of concept demonstrating the technological feasibility of such an installation by comparing its use within different immersive systems: inside all-enclosing HMD or viewed on a monitor. The work therefore does not directly deal with usability and user performance in a pure VR setup but rather compares between an immersive and a nonimmersive one, which clearly offers no insight about its viability as an interaction device for VR. Another smart home application, based on motor imagery, was presented in Leeb et al. (2008). All of these systems require humans to undergo extensive training periods in order to gain reasonable control over the device and in this context it should be pointed out that BCI control has been identified as a skill that needs to be learned, practiced, and maintained (Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002). Bayliss and colleagues compared the P300 interface in three VR setups: a monitor and a static camera and interactive scene delivery inside a head mounted display (HMD). The virtual apartment used for the study offered a total of five actions, and although participants reported better performance in the fully immersive environment, results showed no significant differences between the three display conditions. In games or game-like scenarios, BCIs have been used for binary control in a task involving balancing a virtual character (Lalor et al., 2005) or for control of virtual airplanes (Middendorf, McMillan, Calhoun, & Jones, 2000).

Another interesting set of experiments was carried out using a method based on motor imagery in order to navigate through a VE. Several experiments showed that imagined movements sufficed to control the trajectory of a virtual character in different environments (Pfurtscheller et al., 2006; Leeb et al., 2004; Leeb, Scherer, Keinrath, Guger, & Pfurtscheller, 2005; Leeb, Settgast, Fellner, & Pfurtscheller, 2007; Friedman et al., 2007; Leeb et al., 2008).

In these studies, EEG activity was captured from the sensorimotor cortex and, over extended training periods, the system learned to classify the participants' motor imagery patterns of hand or foot movement, which in turn could be used for locomotion. Motor imagery was also exploited in controlling a virtual car (Zhao, Zhang, & Cichocki, 2009).

A slightly more unusual example combines motor imagery with the so-called rubber hand illusion (Botvinick & Cohen, 1998). The work demonstrates that motor imagery used to control movements of a virtual arm apparently attached to one's body leads to the illusion of ownership over that arm even though other multisensory correlations such as tactile stimulation were absent during the experimentation phase (Perez-Marcos, Slater, & Sanchez-Vives, 2009).

These more recent examples of BCI applications in VR may be slowly uncovering a new method for HCI, one that only requires thought to effect actions, even though bit rates still remain fairly low at present. Also, the overwhelming majority of BCI studies carried out in VR involve navigation tasks with participants and are ultimately aimed at rehabilitation where VR is only used as a tool to visualize success. Little work has otherwise been done to specifically test BCI performance in VEs.

While it is true that at present only severely disabled people can seriously benefit from the use of a BCI, this is very likely to change in the near future. The advent of commercial BCIs for gaming, as mentioned above, shows that there exists the technical potential as well as public interest to use such devices. Next-generation gaming devices are likely to adopt this trend and in the medium term they will be used for more conventional activity and partially replace current UIs.

3 Materials and Methods

3.1 Materials

For the BCI condition, we used a g.EEGcap to mount eight electrodes to the participant's head. These, in turn, were attached to a g.MOBIlab+ for biosignal acquisition and wireless Bluetooth transmission. The g.MOBIlab+ is a small device that can be carried around the belt, allowing its wearer to move around freely in the laboratory. A proprietary MATLAB/Simulink model was used for acquisition, analysis, and classification of the EEG data. The algorithm essentially detects the most likely P300 response during each iteration and associates it with the signal highlighted 300 ms before. The candidate responses are accumulated and evaluated at the end of each cycle. There should be one candidate for each iteration and the operation with the highest number of candidates is selected and a decision is formed.[2]

The P300 interface is displayed on a separate computer screen and throughout the experiments we used a laptop monitor. The VE is displayed on a 3 × 2 m powerwall and the human head is tracked via a 6 DOF Intersense IS900 motion tracker, attached to a pair of passive stereo glasses that are worn by the participant in order to perceive the scene in 3D. Also, it was important that the glasses did not impede the perception of the P300 flash cycles displayed on the other screen and this was tested during trials.

Since the experiment was not self-paced, participants could neither choose the order of the tasks nor the pace of the experiment, and to partially compensate for this we implemented a function that allowed them to pause the current task. By exploiting the fact that participants wear a head tracker and knowing the rough position and orientation of the P300 display, we could infer whether they were looking at the display or not. This is

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[2] The entire EEG capturing suite including software was provided by g.tec OEG.

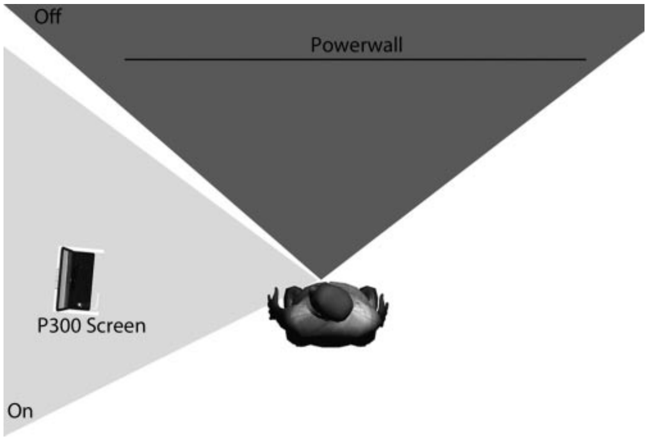

Figure 1. *Experimental setup. When facing the P300 screen to the left starting at an angle of roughly −45° from the powerwall, the P300 will activate and remain active while its user is facing in that general direction (light gray area, on). When facing away from the P300 and onto the powerwall (dark gray area, off), the P300 interface is switched off until the person faces his or her gaze back onto the P300 screen. This ensures that he or she can visually and to some extent physically explore the VR without effecting undesired actions.*

not the case for many BCI applications, and most P300-based systems struggle to offer a simple option to switch the device on or off other than through a symbol in the display itself.

In order to provide such a method, we simply intersect the view plane normal (VPN) with the quadrilateral defined by the position, size, and orientation of the P300 screen. If the ray and quadrilateral intersect, the person is looking at the P300 screen and otherwise away from it, possibly focusing on any part of the VE displayed on the powerwall. If the display is fixed at a certain position and angle relative to the powerwall, this task is trivial; otherwise, we require another 6 DOF tracker to track the position and orientation of the P300-display. For a complete overview of the setup, refer to Figure 1.

For the second condition, we replaced the BCI with a gaze-based interaction procedure that included navigation using an IS900 wand (see next section and Figure 3 for details).

3.2 Virtual Environment

A virtual apartment was built using 3D Studio Max and rendered in XVR (Carrozzino, Tecchia, Bacinelli, Cappelletti, & Bergamasco, 2005). It was composed of a corridor, bathroom, kitchen, living room, and bedroom (see Figure 2). In addition, there were a number of appliances whose states could be altered interactively either by using the BCI or the gaze-based approach (see Figure 3). In total, the BCI condition consisted of more than 200 commands that could be triggered from seven distinct matrices including one for navigation.

3.3 Methods

3.3.1 Variables. We conducted a between-groups study where the independent variable was the input method, either BCI or gaze-based interaction. The dependent variable we observed was the reported sense of presence. Although we also recorded performance results, they did not play an important role in these experiments. Usability and performance of the BCI condition were discussed in previous work (Edlinger et al., 2009; Guger, Holzner, Groenegress, Edlinger, & Slater, 2009).

3.3.2 Population. A total of 24 healthy and naïve participants took part in our study, 12 in each condition. They were aged 19–36 (25 ± 4.7 years). Eleven participants were female and 13 were male and all of them had normal or corrected to normal vision. The 12 participants who took part in the second condition were paid €5 and the entire procedure lasted for about 30 min. Since the BCI condition included a substantial training period lasting approximately 90 min and another approximately 40 min to complete the experiment, the 12 participants in that condition were paid €15 for their participation.

3.3.3 Procedure. Both conditions were guided and participants were asked to complete a given set of tasks in a certain order. Given the different interaction

Figure 2. *Bird's-eye view and living room of the virtual apartment.*

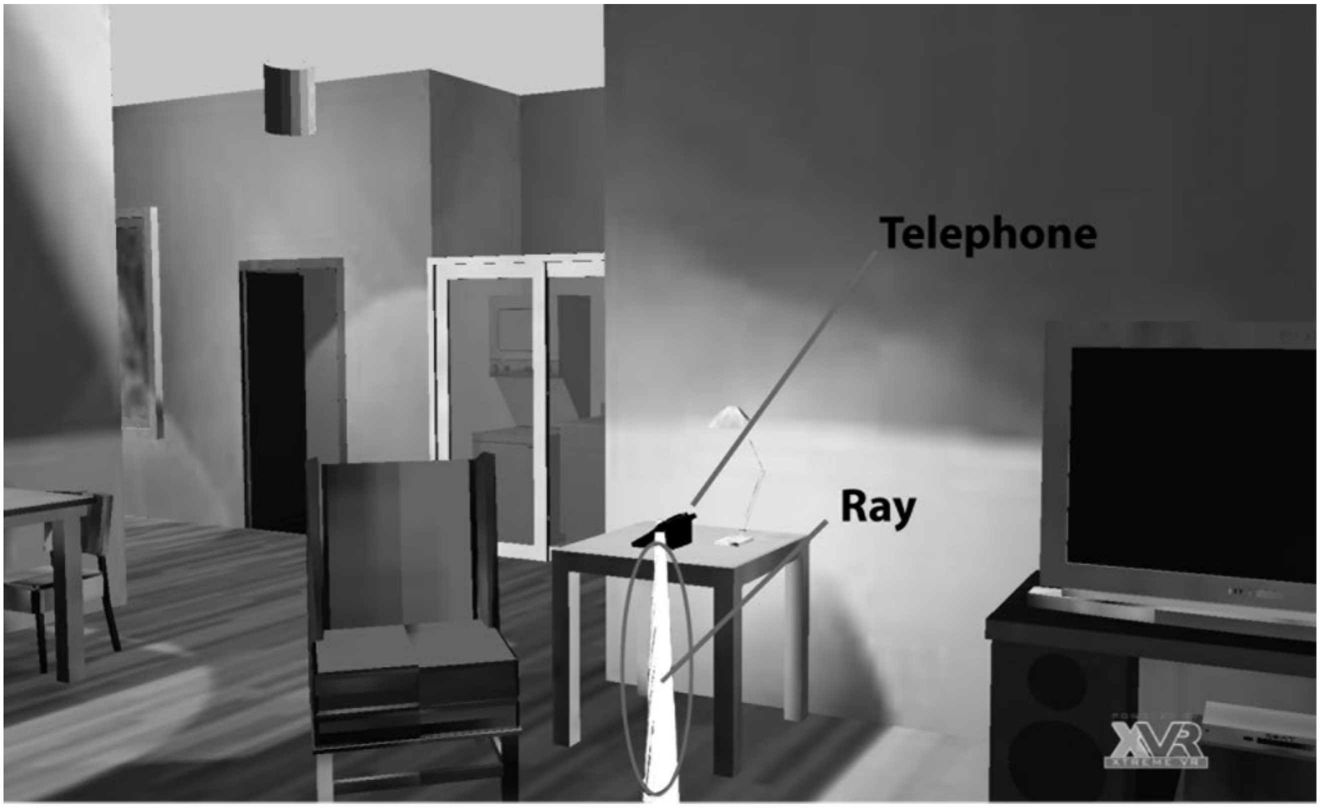

Figure 3. *Adapted version of the smart home using gaze-based interactions. In this example, the ray intersects with the telephone (shaded black for clarity) and resting the ray (shaded white) on the object for a few seconds will operate it.*

methods, the tasks and the task order were kept as similar as possible although some variations were inevitable. These variations arose due to the BCI sometimes requiring a selection of different interaction matrices in order to complete the next task, whereas in the gaze-based approach the task could be completed by using a combination of head rotations and wand navigation. Locomotion was therefore difficult to represent in discrete steps in the second study.

Table 1 gives an overview of the order and the differences between the two conditions.

Note also that in the BCI condition, the icon corresponding to each ensuing task was presented in the P300 display a few seconds ahead of each cycle. In the gaze-based condition, tasks were displayed as text on the powerwall.

The BCI condition and performance results are discussed in detail in Edlinger et al. (2009). Briefly, a P300 classifier was trained for each of the seven P300 matrices before the trial began. During training, 15 iterations were used for classification and trials consisted of repetitions of the tasks in eight, four, and two iterations, respectively. User performance was recorded and in addition participants were asked to fill in a questionnaire consisting of five questions, each on a 7-point Likert scale (see Table 2 for the breakdown of each question) with the scores adjusted for the analysis. Three more questions specifically invited participants to comment on the experience.

A similar procedure was repeated for the second condition. There was an initial training environment in which participants could familiarize themselves with the wand navigation and use of the buttons. The environment consisted of a warehouse-type building with several different-colored cones that each had to be activated in a certain order. An object could be activated by intersecting it with the ray visualizing the person's direction of gaze, i.e., by looking at the object (cf. Figure 3).

Table 1. *Overview of Gaze-Based Task Sequence and Comparison with BCI Operations**

	Gaze-based	BCI
1	Open front door	Open front door
2	Go to living room (wand)	(a) Select 'Movement' matrix (b) Rapid forward (c) Turn right (d) Select 'Main' matrix (e) Select 'Goto' matrix (f) Go to location 'C'
3	Play music	(a) Select 'Music' matrix (b) Play
4	Toggle light	(a) Select 'Light' matrix (b) Toggle light
5	Switch on air-conditioning	(a) Select Temperature matrix (b) Switch on air-conditioning
6	Stop music	(a) Select 'Music' matrix (b) Stop
7	Switch on TV	(a) Select 'TV' matrix (b) Switch on TV
8	Switch off TV	Switch off TV
9	Use telephone	(a) Select 'Phone' matrix (b) Make call
10	Switch off air-conditioning	(a) Select 'Temperature' matrix (b) Switch off air-conditioning
11	Go to bedroom (wand)	(a) Select 'Goto' matrix (b) Go to location 'V'
12	Close bedroom door	Close bedroom door

*The number of necessary operations—except for navigation which cannot be exactly quantified—is greater for the BCI due to switching between interaction matrices, and 11 out of the 23 tasks involve changing from one to another.

4 Results

Although our main focus was on comparing self-reported presence scores, for completeness the mean performance in the gaze-based condition was 64%, almost the same as the average of the BCI condition, which was 67%. Performance was taken to be the rate of correct decisions per task. If a task was executed incor-

Table 2. *Means, Standard Deviations and Nonparametric Rank Sum Test for Presence Questions in Both Experiments*

Question	Presence scores with BCI (n = 12)		Presence scores with gaze/wand (n = 12)		
	Mean	*SD*	Mean	*SD*	*p* values
Q1 To what extent did you feel like you were in the virtual apartment? (1 = not at all, 7 = most of the time)	3.0	1.64	4.5	1.88	.0496
Q2 To what extent were there moments during which you felt the apartment was real? (1 = never, 7 = most of the time)	2.92	1.51	3.92	2.15	.1663
Q3 Do you think of the apartment as an image you saw or as a place you visited? (1 = an image, 7 = a place)	2.58	1.12	4.25	2.1	.0405
Q4 During the experience did you feel you were in an apartment or in a laboratory? (1 = in laboratory, 7 = in apartment)	2.91	2.0	4.83	1.85	.0426
Q5 During the experience did you think a lot you were inside a laboratory or were you absorbed by the apartment? (1 = in the laboratory the majority of the time, 7 = hardly ever)	2.75	1.57	4.58	1.78	.0204

rectly, the system would automatically advance to the subsequent task. For more details on performance, refer to the additional material presented elsewhere (Edlinger et al., 2009; Guger et al., 2009).

In both conditions, we asked participants to fill out a short questionnaire containing five quantitative presence questions on a 7-point Likert scale plus three questions inviting the participant to comment on specific points relating to the experience. The questions (translated from Spanish) are summarized in Table 2; mean and standard deviation scores are given where applicable. The meanings of the numeric indicators 1 to 7 are also indicated in the table.

If we take the five presence questions (Q1 to Q5) and compute the number of questions for which the score is greater than or equal to 5 (out of 7), we obtain a new variable *y:*

BCI condition	$mean(y) = 0.83$	$SD(y) = 1.53$
Gaze-based condition	$mean(y) = 2.67$	$SD(y) = 1.83$

A nonparametric rank sum test rejects the hypothesis of equal medians (p = .012). If we consider each question individually then the rank sum test results in the data presented in the last column of Table 2, and it is clear that for every question, the mean for the gaze and wand method is higher than for the BCI method.

5 Discussion

With respect to the difference in performance between the BCI and gaze-based condition, it may be possible that some tasks were somewhat ambiguous in the second condition. When asked to open the bedroom door, for example, all but one participant opened the terrace door instead. This has to do with the participants not knowing the exact layout of the apartment, which was the same as in the BCI condition. In addition, unlike the BCI condition, participants had to be in line of sight of the objects and maintain a certain proximity in order to trigger them. Choosing the wrong object for those reasons is therefore not a problem that arises in a BCI-type interaction, because it is not necessary to know the exact location of an object in order to trigger it. Neither is it necessary to be in line of sight. Position in virtual space and knowledge about it become largely independent of the task when using the BCI using the method adopted in our study. Once an object is chosen from the list, it is triggered irrespective of whether the BCI user knows where it is or whether he or she is close by. In this sense, and although it requires a lot more training, it is a much simpler interface that is less demanding regarding prior knowledge about the environment and the objects it contains.

Regarding the reported presence scores in the P300-based BCI study, they alone are interesting because they are overwhelmingly low. This could mean either that the workload required for operating the BCI was too high or that participants failed to register the VE and the apartment. However, about a third of the participants commented on question 6 ("How did you feel during the experience") that they liked the visual appeal of the apartment, so there is no doubt that they were aware of at least some aspects relating to its realism. One participant, though, explicitly stated that the BCI required too much visual attention. It is possible, therefore, that merely allowing participants to control the state of the BCI by looking at or away from the screen was either not a sufficiently clear procedure or switching between two different displays was too confusing. Our own observations during individual trials, however, show that people were frequently switching back and forth between P300 and powerwall. Note also that they were located about 1.5 m away from the powerwall, which covered almost the entire field of view when being faced directly. Thus, use of a P300-driven BCI in our arrangement seems to negatively affect presence.

Another possible explanation for the low scores relates to other areas of presence theory. There are some theories of presence that tend to equate action, action potential, or correlation between action and an expected and detectable outcome, with the sense of presence (Schubert, Friedmann, & Regenbrecht, 1999; Flach & Holden, 1998; Zahorik & Jenison, 1998). In light of the current study, this may be the case if and only if the action is initiated by means of at least some physical activity. Whether this activity is based on mere button presses and head rotations or, at the other end of the spectrum, more physically engaging approaches, may not be important because compared to interaction using a BCI, most of these depend on a person's physical activity while the BCI is a purely mental procedure. Thus, one reason for the low scores may be the unusual and unfamiliar method of communication compared with more physical means. Some comments point in this direction and one participant stated that "It's weird to realize something [. . .] without any physical interaction. I felt like I was missing something." However, in a previous study where the objective was to move a virtual body by thought by using motor imagery, participants reported the opposite and that the experience became more dreamlike (Friedman et al., 2007).

A fairly novel mode of interaction that uses only thought, therefore, may appear too vague in many aspects and perhaps even bizarre to experienced and frequent users of computers or VEs. To some extent, there is evidence supporting this view and some work demonstrates that a substantial part of our self-perception and recognition is obtained from action (Rochat, 1998; van den Bos & Jeannerod, 2002), which is physical in nature, and it is possible there is simply not enough correlation between the physical action and the process of executing it, that is, the action is not imagined but achieved by counting repeated occurrences of a symbol representing that action.

In this light, we can claim that from the point of view of the BCI user, there are no physical actions associated with its use. This is because, unlike real physical actions (that may have previously been learned, for example, moving the mouse to the left in order to move the cursor on the computer screen to the left), using a BCI completely lacks physicality and thus may not be regarded as a physical activity or skill because it does not involve motor activity. On the other hand, a recent study on inducing the rubber hand illusion through motor imagery showed that body ownership was produced in many participants (Perez-Marcos et al., 2009) with similar results to the original study (Botvinick & Cohen, 1998). However, motor imagery is a much more active type of BCI than the rather passive and responsive P300 interface and thus may be more similar to actual physical action than the use of the P300.

Using a P300-based BCI implies that no prior knowledge is needed about the virtual environment and, worse, no knowledge about it may be gained from using it. Tasks can be completed via the P300 interface and projected into the VE but no knowledge about it is needed in terms of navigation or many other points of reference. Therefore, an essential lesson to be learned from our experiments is that in order for P300-based BCIs to be employed in a VR, they need to force the users to make inferences about the space, which remains otherwise completely detached from what they are in fact doing: they are looking at a matrix of symbols representing a set of actions. But if this action has no measurable consequence for the user, either regarding performance or any other way, and if any knowledge or information about the virtual space makes no difference in the action-selection process, it can be ignored. This is in contrast with the second experiment in which locomotion and action were both tightly coupled with the virtual space and thus spatial knowledge had to be constructed in order to solve the tasks. This resulted in the reported presence scores being much higher in the second study.

6 Conclusions

We presented a complementary study assessing the effects of BCI use on presence. We measured presence in two task-oriented studies with different interaction methodologies but otherwise comparable setups. One used a BCI for interaction and the other a gaze-based selection approach, which we deemed sufficiently similar to the P300-based interface of the BCI to allow us to compare self-reported presence scores between both conditions.

Quantitative presence scores show that the self-reported sense of presence was significantly higher in the second condition than in the first one. 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.

In a second complementary study, in a single condition we directly tested for this initial hypothesis where only the interaction method was changed to a combination of gaze-based and wand-based operations. The environment and setup remained the same as in the initial experiment. While overall performance rates are very similar in both conditions (i.e., approximately 65%), the reported level of presence was significantly higher in the second study than in the first one. We conclude that this is the result of two issues.

First, the lack of physical action or even relevant thoughts especially during navigational tasks was so unusual and novel to all participants that it resulted in a decisive lack of physicality when viewing the VE. Since all participants were healthy, they quickly found that their physical movements, with the notable exception of head tracking, had little to no effect. This might be an unfamiliar experience to most. The general problem could relate somehow to the fact that P300-based BCI navigation and locomotion completely lacks physical activity. Tasks in the BCI condition could be completed independent of any knowledge about the virtual space, which, in contrast, was vital for completing the gaze-based condition.

Second, high mental workload in the BCI condition rather than the setup itself possibly inhibits people from willingly suspending disbelief. Participants could switch back and forth between P300 interface and VE whenever they wished, and the device would be paused accordingly.

A crucial lesson to be learned from this study is that P300-based BCIs can be operated completely detached from the metaphor upon which they act in a VR or other environment. If no measurable consequences can be detected by its users, then there is no need for them to assess this stream of information. In order to become an effective tool in VR, P300-based BCIs therefore need to force users to make some inference about the virtual space—a central requirement for presence.

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