EFFECTS OF P300-BASED BCI USE ON REPORTED PRESENCE IN A VIRTUAL ENVIRONMENT

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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 discuss two studies assessing how mental workload of a P300-based BCI affects the reported presence of participants in a virtual environment (VE). In the first study we employed a BCI exploiting the P300 event-related potential (ERP) that allows control of over 200 items in a virtual apartment. In a 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 were assessed by means of a short questionnaire. Results suggest that the use of the P300 degrades reported presence in relation to the gaze-based approach. We argue that this is because P300 method employed introduces breaks in presence, does not require participants to understand the space in which the objects they are manipulated are located, and does not mobilize motor action, or even thoughts of motor action, that are relevant to the semantics of the task. We conclude with remarks about the obvious efficiency of the

P300 method as a control device compared with other forms of BCI when used in the context of virtual reality must maintain presence by being embedded in a user-interface that overcomes these three problems.

1. Introduction

Non-invasive BCIs offer a flexible method for instigating many different actions by the use of thought, 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 exist that can, for example, be used as auxiliary controllers for computer games, and research has been quick to adapt to the trend of exploiting BCIs in educational or entertainment applications (Fairclough, 2008, Anton et al., 2008).

Much work has been carried out exploiting the P300-component and motor imagery for navigation and object manipulation in VR (Guger et al., 2008). Thus far, however, no study has addressed the impact of BCI use on presence in virtual environments. In this paper we present the more specific relationship between 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 takes place 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 was used in the same VE.

Previously we reported on an experiment for P300-based BCI for smart home control that used three different conditions varying the number of classifying iterations between eight and two (Edlinger et al., 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 high mental workload that is required to use the BCI. Whatever the cause, it demonstrates that naïve use of P300-based BCIs for interaction in VR potentially undermines the user experience - thus weakening the case for the use of P300-based BCIs and VR for prototyping control of real smart homes, or for applications such as entertainment. In order to have a point of comparison of 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 allow participants to 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 et al. 2007, Cardillo et al., 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 and Donchin, 1988). The P300 ERP has been exploited extensively as a spelling device (Guan et al., 2004, Krusienski et al., 2006, Sellers and 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 et al., 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 efficiency between an immersive and a non-immersive one. 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 et al., 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) for control of virtual airplanes (Middendorf et al., 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 et al., 2005, Leeb et al., 2007b, Friedman et al., 2007, Leeb et al., 2007a). 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 et al., 2009).

A more unusual example combines motor imagery with the so-called rubber hand illusion (Botvinick and 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 et al., 2009).

These more recent examples of BCI applications in VR, may be slowly uncovering a new method for human-computer interaction, one that only requires thought to effect actions, even though bitrates 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 as described in Guger et al. (2009). The algorithm essentially detects the most likely P300 response during each iteration and associates it with the signal highlighted 300ms 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.[1]

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

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 3x2m powerwall and the human head is tracked via a six degree of freedom (6DoF) 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.

The tasks in the experiment were not self-paced - participants could neither choose the order of the tasks nor the pace of the experiment. In order to partially compensate for this we implemented a function that allowed them to pause the current task. By exploiting the fact that participants wore 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 not the case for many BCI applications and most P300-based systems struggle to offer a simple option to switch on or off the device 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 focussing 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 position and orientation of the P300-display. For a complete overview of the setup refer to Figure 1.

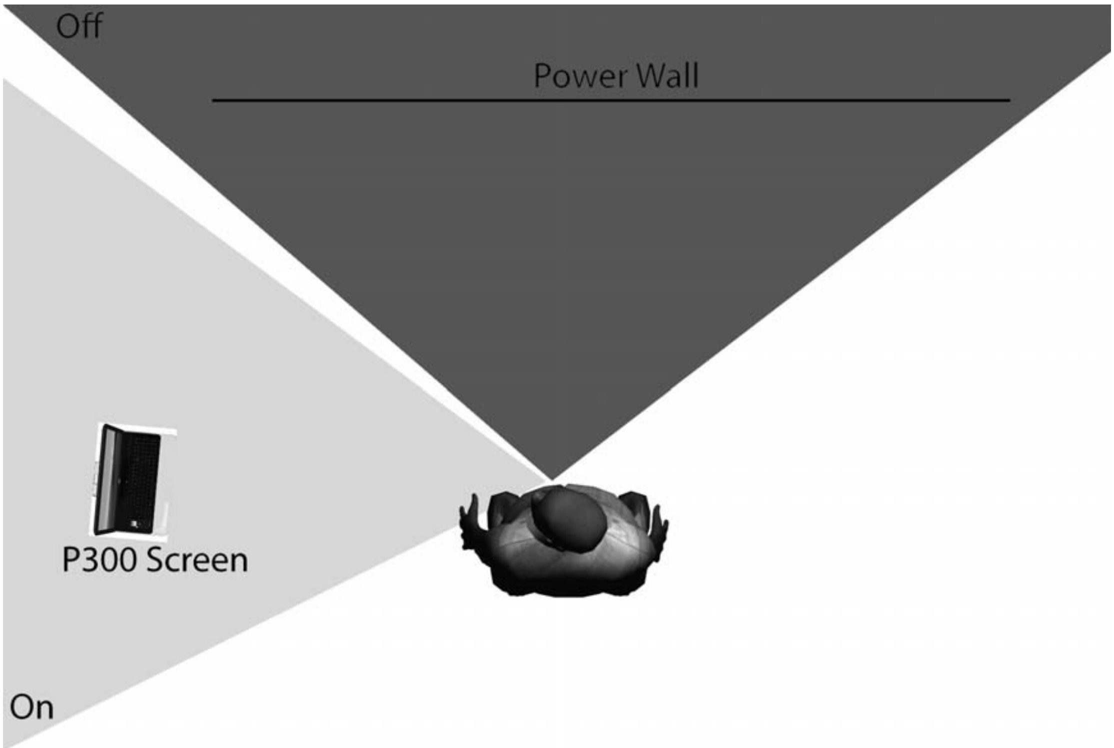

Figure 1. Experimental setup. When facing the P300 screen to the left starting at an angle of roughly -45º from the power wall, the P300 will activate and remain active while its user is facing in that general direction (light grey area, On). When facing away from the P300 and onto the powerwall (dark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

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 4 for details).

3.2 Virtual Environment

A virtual apartment was built using 3D Studio Max and rendered in XVR (Carrozzino et al., 2005). It comprised a corridor, bathroom, kitchen, living room and bedroom (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. In total, the BCI condition consisted of more than 200 commands that could be triggered from seven distinct matrices including one for navigation. Figure 3 shows two examples of P300 masks.

Figure 2 Birds-eye view (left) and living room (right) of the virtual apartment.

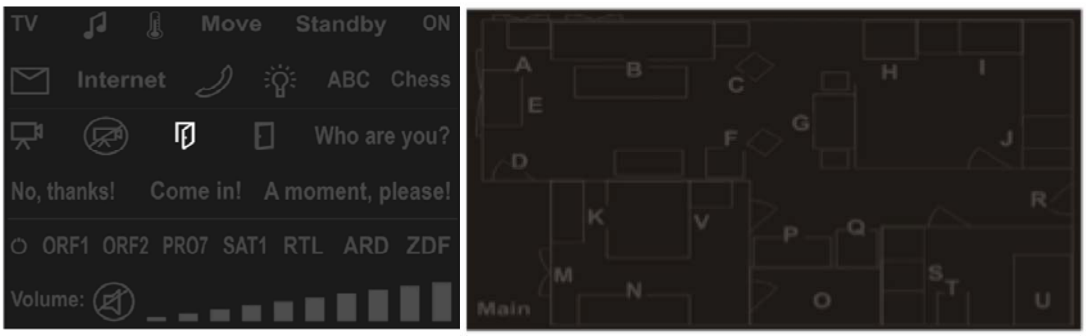

Figure 3. Left: The control mask with the main menu in the first 2 rows, the icons for the camera, door control and questions in the 3rd and 4th row and the TV control in the last 2 rows. Right: Control mask for going to a specific position in the smart home. The mask gives a bird’s eye view of the apartment with characters at specific positions.

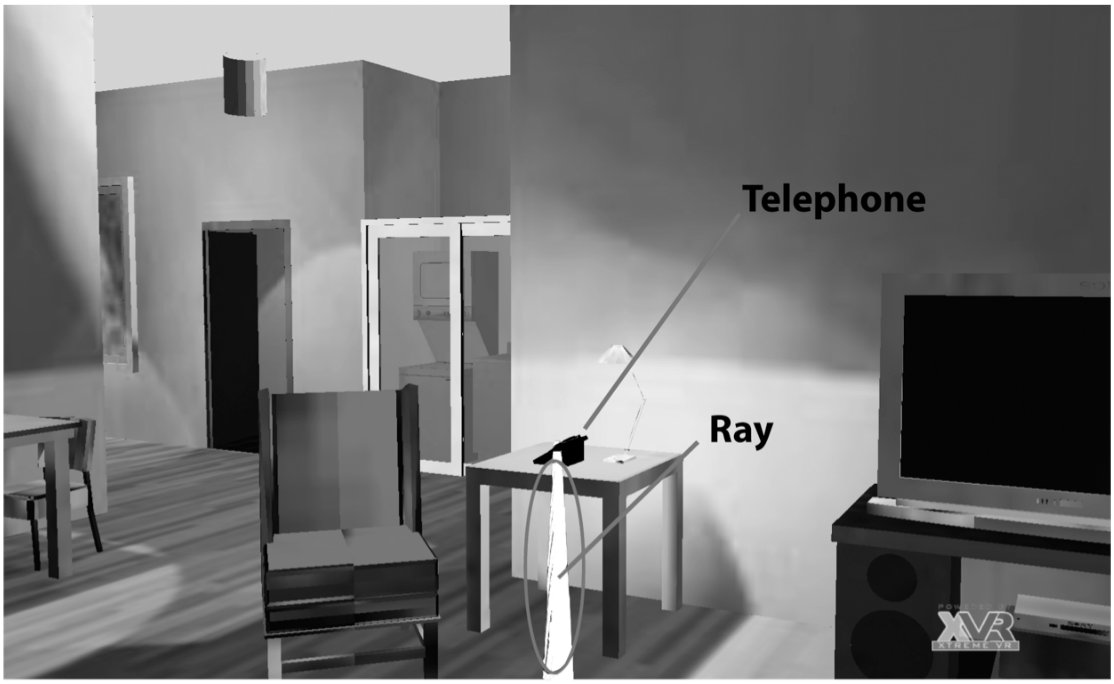

Figure 4. Adapted version of the smart home using gaze-based interactions. In this example the ray intersects with the telephone (shaded black for clarity) and resting the ray (shaded white) on the object for a few seconds will operate it.

3.3 Methods

(a) 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. Usability and performance of the BCI condition, discussed in (Edlinger et al., 2009, Guger et al., 2009), are not the concern of the current paper.

(b) Population

A total of 24 healthy and participants took part in the first (P300) condition who were inexperienced in BCI. They were aged 19-36 (mean and standard deviation 25±4.7) years. Eleven participants were female and thirteen were male and all of them had normal or corrected-normal vision. The 12 participants who took part in the second (gaze-based) condition were paid 5€ and the entire procedure lasted for about 30 minutes. Since the BCI condition included a substantial training period lasting approximately 90 minutes and another approximately 40 minutes to complete the experiment, participants in this condition were paid €15 for their participation.

(c) Procedure

Both conditions were guided in the sense that participants were asked to complete a given set of tasks in a certain order. Given the different interaction methods the tasks and the task order were kept as similar as possible between the two conditions although some variations were inevitable. These variations arose due to the BCI sometimes requiring selection of different interaction matrices in order to complete the next task whereas in the gaze-based approach it 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.

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 (a light mask, a music mask, a phone mask, a temperature mask, a TV mask, a move mask and a go to mask) before the trial began. During training 15 iterations were used for classification and trials consisted of repetitions of the tasks in 8, 4 and 2 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).

Table 1. Overview of gaze-based task sequence and comparison with BCI operations. 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.

	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

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 training environment consisted of a warehouse-type building with several different-coloured cones that had to be "activated" in a certain order by intersecting the pole with the object. The experimenter also guided this step.

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 BCI condition, which was 67% (the average over all subjects for 8, 4 and 2 flashes thus excluding the training period).

In both conditions we asked participants to fill in a short questionnaire containing five presence questions on a 7-point Likert scale plus 3 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 5 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.

For BCI condition $mean(y) = 0.83$ $sd(y) = 1.53$

For gaze-based condition $mean(y) = 2.67$ $sd(y) = 1.83$

A non-parametric rank sum test rejects the hypothesis of equal medians for y (P = 0.012). If we consider each question individually then the rank sum test results in the data presented in the last column of Table 2.

Table 2. Means, standard deviations and non-parametric rank sum test significance levels for the difference between the questionnaire scores in the two experiments. The individual scores range between 1 and 7.

	Presence scores with BCI (n=12)		**Presence Scores with gaze/wand (n=12)**		**P-values**
Question	**Mean**	**SD**	**Mean**	**SD**	
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	0.0496
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	0.1663
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	0.0405
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	0.0426
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	0.0204

5. Discussion

With respect to the small difference in performance between the BCI and gaze-based condition, it may be possible that some tasks were somewhat ambiguous in the second one. Unlike the BCI condition participants in the gaze-based experiment had to be in line of sight of the objects and maintain some proximity in order to trigger them. Choosing the wrong object for those reasons is 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 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. However, this benefit for BCI in terms of task performance is also a detriment in terms of maintaining presence, since participants do not have to understand the space in which they are triggering actions.

Regarding the reported presence scores in the P300-based BCI study, they alone are interesting because they are overwhelmingly low. This could mean that either the workload required for operating the BCI was too high and 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 even though they were located about 1.5m away from the powerwall which filled almost their entire field of view when facing it directly. Thus it is the very use of a P300-driven BCI in our arrangement seems to negatively affect presence.

This fits in very well with the idea of 'breaks in presence' (BIPS) (Slater and Steed, 2000). A BIP is when some event occurs that results in a temporary intrusion of the real world of the laboratory into the VE experience – classic examples being glitches in rendering, entanglement in cables, failures in tracking, breaks in the display (Slater et al., 2006), and others. In the 2000 paper it was shown that the number and distribution of BIPs was negatively correlated with reported sense of presence. Having to look outside the field of view of the VE in order to stare at a display monitor that is clearly not part of the VE is a BIP-inducing event. Since these events had to occur in order to be able to complete the assigned tasks the prediction would be a low overall reported presence score.

It is important to realise that participants performed the tasks with the P300 system as fast as possible. They had the opportunity to halt the P300 system in order to look at the virtual smart home, but normally they just had a quick look at the result of their selection and went back to the P300 display to perform the next task. Furthermore the possible selection speed of the BCI was tested with 8-, 4- and 2-flashes only per character. If the P300 system would be controlled with more flashes, as during the training period, then it would be likely to be less stressful for the participant attempting to avoid errors. When the number of flashes is reduced, the performance speed is increased but the concentration on the task must also be higher. Therefore we were pushing the P300 to an extreme, resulting in a reduction of the sense of presence.

Another possible explanation for the low scores relates to another aspect 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 et al., 1999, Flach and Holden, 1998, Zahorik and Jenison, 1998, Slater, 2009). In light of the current study, this may be the case if and only if the action is effected by means of at least some physical activity. Whether this activity based on button presses and head rotations or 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, another 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 that the experience became 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 bizarre. To some extent there is evidence supporting this view and there is work that demonstrates that a substantial part of our self-perception and recognition is obtained from action (Rochat, 1998, van den Bos and Jeannerod, 2002), which is physical in nature and possibly there is simply not enough correlation between the physical action and the process of executing it, i.e. 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 because unlike real physical actions that may have previously been learned, e.g. 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 may thus not be regarded as a physical activity because it does not involve explicit motor action. 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). However, motor imagery is a much more active type of BCI than the P300 interface, engaging the same parts of the brain as in real movement, 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 little knowledge about it may be gained from using it. 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 consequences in terms of experience of being and acting in a space, then the action becomes a purely formal act, a manipulation of symbols. 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 achieve the tasks which may be why the reported presence scores were higher in the second study.

6. Conclusions

We have presented the results of a new experiment that attempts to provide insight as to why a BCI method for smart home control resulted in unusually low reported presence scores. We measured reported presence in two task-oriented studies with different interaction methodologies but otherwise comparable setups. One used a P300 BCI for interaction and the other a gaze-based selection approach comparing self-reported presence scores between both conditions.

The reported sense of presence scores were generally higher in the second condition than in the first one. We postulate four principle reasons for this. First, that the P300 method that was used inevitably results in breaks in presence, since participants had to look outside of the VE in order to accomplish their task. Second, in the P300 condition participants did not need to construct an internal model of the space nor gain direct active knowledge of the space in order to select actions. In the gaze-based study, many actions could not be performed without active exploration of the space (e.g., in order to have line-of-sight to an object to be manipulated). Third, the type of activity that participants engaged in to accomplish tasks in the P300 did not involve any motor action relevant to the task, but only essentially an abstract manipulation of symbols. This breaks the requirement that presence requires physical action, and may also account for why motor imagery based BCI does not apparently result in lesser reported presence – since at least here the type of thoughts that participants must generate can be directly related to motor action (e.g., thinking of moving the feet in order to locomote (Leeb et al., 2007b)).

A P300 based BCI system is optimally suited to control smart home applications with high accuracy and high reliability. Such a system can serve as an easily reconfigurable and therefore cheap testing environment for real smart homes for handicapped people. However, a crucial lesson to be learned from this study is that when operating a P300-based BCI in the context of a VE actions can completely detached from the spatial information and objects upon which they act. Hence ‘presence’, the feeling of being in the place in which the actions are effected, becomes compromised, since participants may not become even become properly aware of the very place in which they are operating. In order become an effective tool in VR, P300-based BCIs therefore need to force users to have some direct knowledge of the virtual space – a central requirement for presence. This is fundamentally a problem of finding the right kind of user interface that embeds P300 use in VR within a presence-oriented framework.

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