CONTROLLING A VIRTUAL BODY BY THOUGHT IN A HIGHLY-IMMERSIVE VIRTUAL ENVIRONMENT

A Case Study in Using a Brain-Computer Interface in a Virtual-Reality Cave-like System

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Abstract: A brain-computer interface (BCI) can arguably be considered the ultimate user interface, where humans operate a computer using thought alone. We have integrated the *Anon*-BCI into a highly immersive Cave-like system. In this paper we report a case study where three participants were able to control their avatar using only their thought. We have analyzed the participants' subjective experience using an in-depth qualitative methodology. We also discuss some limitations of BCI in controlling a virtual environment, and interaction design decisions that needed to be made.

1 INTRODUCTION

Brain-computer interface (BCI) has been studied extensively as a tool for paralyzed patients, which may augment their communication with the external world and allow them better control of their limbs. However, once it has been developed for these critical applications, we expect it will have profound implications on many other types of user interfaces and applications.

BCI could be one of the most significant steps following "direct manipulation interfaces" (Schneiderman, 1983) – where intention is mapped directly into interaction, rather than being conveyed through motor movements. Furthermore, if used in an immersive virtual environment (IVE) this could be a completely novel experience and, in the future, lead to unprecedented levels in the sense of presence (for recent reviews of the concept of presence see (Vives and Slater, 2005) and (Riva et al., 2003)).

A key requirement for a successful experience in an immersive virtual environment (IVE) is the representation of the participant, or its avatar (Pandzic et al., 1997; Slater et al., 1994; Slater et al., 1998). This paper describes the first ever study where participants control their own avatar using only their thoughts. Three subjects were able to use the *anon*-BCI to control an avatar, and their subjective experience was assessed using questionnaires and a semi-structured interview. Naturally, a third-person avatar, such as used in this experiment, is only one possible interface to an IVE.

Using a BCI to control an IVE by thought raises several major human-computer interaction (HCI) issues: whether classification of thought patterns is continuous (asynchronous BCI) or only takes place in specific moments (synchronous BCI), the number of

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input classes recognized, the importance of feedback, and the nature of the mapping between thoughts and resulting action in the IVE. In this paper we refer to these issues, and present a case study that specifically addresses the issues of feedback and mapping.

A critical initial hypothesis is that natural mapping between thought processes and IVE functionality would improve the experience. A one-to-one mapping seemingly makes intuitive sense, but having this mapping is constraining because we are limited in the scope of thought patterns that we can detect based on contemporary brain recording techniques. In addition, it precludes other more complex or more fanciful body image mappings; what if we want to experiment with lobster avatars? (See Jaron Lanier's "everyone can be a lobster" statement in http://www.edge.org/q2006/q06_7.html#lanier). In the case study reported here we have found out that natural mapping was reported to feel more natural and easy than when the mapping was reversed. However, the results do not indicate that BCI accuracy was better with natural mapping than with reversed mapping.

The main implication of our case study is that this new type of interface, whereby IVE participants control their avatars by thought, is possible, and should be further pursued. In addition, we reveal new insights about the HCI issues that are involved in such an interface, and provide a first glance into what the experience of using such an interface may be like.

2 BACKGROUND

The possibility that people may be able to control computers by thought alone, based on real-time analysis of electroencephalogram (EEG) waves, was already conceived as early as the 1970s (Vidal, 1973). Recently, with advances in processing power, signal analysis, and neuro-scientific understanding of the brain, there is growing interest in BCI, and a few success stories. Current BCI research is focussing on developing a new communication alternative for patients with severe neuromuscular disorders, such as amyotrophic lateral sclerosis, brainstem stroke, and spinal cord injury (Wolpaw et al., 2002).

Previous research has established that a BCI may be used to control events within an IVE. One thread of research tried to evaluate BCI as an additional control channel for future combat pilots (Nelson et al., 1997; Middendorf et al., 2000). Bayliss et al. studied BCI based on the P3 evoked potential (EP) in the context of a virtual reality driving simulation and a simulation involving operating a few devices in a virtual apartment (Bayliss and Ballard, 2000; Bayliss, 2003).

This previous research into IVE and BCI was all based on several types of visually evoked responses. Our research is based on a different BCI paradigm that exploits motor imagination. Such a motor imagination would, for example, be thinking about moving a hand or a foot, but without actually moving it (Pfurtscheller and Neuper, 2001).

In a previous experiment (Anonymous,), we have allowed subjects to navigate a virtual street using BCI in a Cave-like (Cruz-Neira et al., 1992) system. Our results in that previous experiment provided some evidence that a highly immersive environment such as a Cave may not only improve user motivation, but may also facilitate BCI accuracy. This suggests that there is a great potential in using IVEs with BCI. However, our research has also made us aware of the many limitations and design issues that come into play when using BCI as an interface to control and IVE, which we now consider.

The first issue is the number of different events (or classes) distinguished in real-time, through the analysis of EEG. As we add more classes, accuracy quickly drops, and the number of EEG channels (recorded brain areas) needs to grow, which makes the sessions more complex and time consuming. Another limitation is that BCI is often synchronous, or trigger-based, i.e., the classification is not applied continuously, but only in specific time windows following an external cue, such as a short sound after which participants are required to have the appropriate thoughts. Asynchronous BCI is possible, but accuracy is compromised (Millan and Mourino, 2003).

Wolpaw et al. highlight the importance of feedback for BCI (Wolpaw et al., 2002). In order to be effective, the feedback needs to be immediate. However, providing continuous and immediate feedback causes a problem. If we look at the accuracy of classification over time, we see that there is typically a delay of 1-3 seconds between the onset of the trigger and the optimal classification. The typical approach, which we also adopt here, is to provide immediate, continuous feedback, for the whole classification duration (approximately four seconds), even though we know the classification is rarely correct throughout this whole duration. Figure 1 shows the data from a typical training run: in this case the classification rate reaches an optimum 2-3 seconds after the trigger, and then drops again.

A natural question is whether a more direct mapping between the type of thought required to initiate an action and the feedback from that thought would improve BCI performance, and how this mapping would be experienced by the participants.

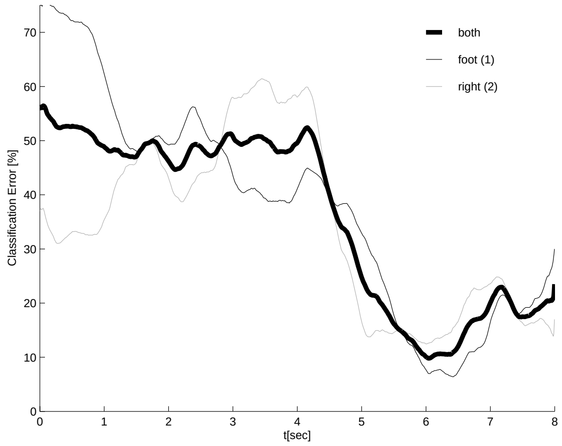

Figure 1: Classification error over time, averaged over 40 triggers in one run. A cross is displayed from time 0, and an arrow cue is given at second 3 for a duration of 1.25 second, which indicated to the subject what they should "think".

3 METHOD

We have opted to use a basic *anon*-BCI paradigm, which is binary and synchronous. This entails limited information throughput, but increases subjects' BCI success rate, which is thus appropriate for a first-of-its-kind research.

3.1 Subjects and Training

Eleven subjects went through "traditional" (2D, monitor-based) BCI training, and the top three were selected for the actual IVE study. This is a typical BCI screening process. It is known that a small percentage of population can easily adapt to the BCI and a larger majority can reach similar accuracy levels, but only with long periods of training (Guger et al., 2003), thus typically 2-5 subjects are used to prove the feasibility of a system. Since we were also interested in comparing between two conditions, we had each subject repeat each condition four times.

Each subject first took part in a number of training runs without feedback. In each run the subject had to imagine a movement of both their legs or a movement of their right hand in response to a visual cue stimulus presented on a computer monitor, in the form of an arrow pointing downwards or to the right, respectively (Figure 2). In addition to the visual cue an auditory cue was also given either as a single beep (hand imagination) or as a double beep (legs imagination). Each trial started with a fixation cross (second 0) followed at second 3 by the cue-stimulus presented for 1.25 seconds. There was a random duration interval of 0.5-2 seconds between the trials.

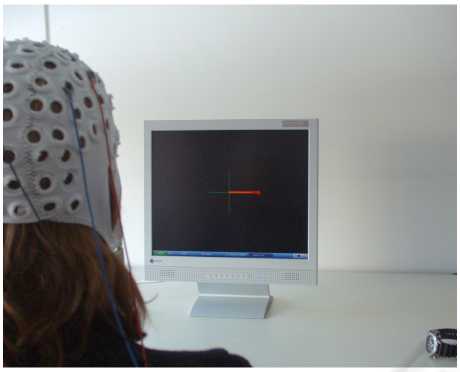

Figure 2: "Traditional" BCI in front of a monitor: the arrow on the red cross indicates to the subject whether they should imagine moving their hand or their feet. Subjects need to keep concentrating on this thought as long as the cross is displayed; for 4.25 seconds.

Forty EEG trials, twenty for every class, were recorded in one run. The EEG trials from runs without feedback were used to set up a classifier for discriminating between the two different mental states. In further runs, visual feedback in the form of a moving bar was given to inform the subject about the accuracy of the classification during each imagination task (i.e., classification of right-hand imagination was represented by the bar moving to the right, classification of feet movement imagination made the bar move downward; see Figure 3). The training and feedback runs were repeated a number of times over a period of a few weeks, until a satisfactory classification for the discrimination between the two motor imagination tasks was achieved. Each session, composed of a number of runs, lasted approximately two hours.

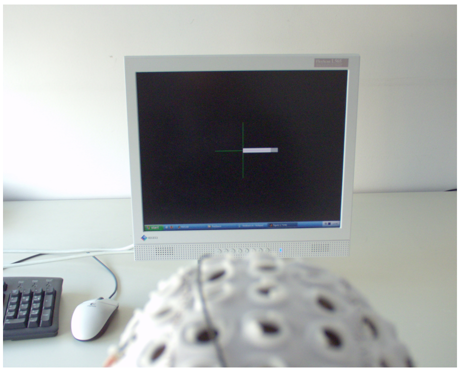

Figure 3: "Traditional" BCI in front of a monitor: the white bar provides immediate and continuous feedback for 4.25 seconds.

Two subjects had a high BCI success rate in their first few runs: one had over 85% accuracy and the other over 90% accuracy. Finding a third subject was more difficult. After a few weeks of training, three other subjects reached approximately 75% accuracy, showing improvement over time, but the improvement was slow.

Eventually, the study proceeded with three subjects: two females and one male (aged 21,49, and 27, respectively). All subjects were right handed, without a history of neurological disease. Subjects gave formal consent to participate in the study, and were paid the equivalent of $12 per hour. Each session lasted 3-4 hours, and each subject went through two sessions.

3.2 EEG Recording

Three EEG channels were recorded bipolarly (two electrodes for each channel). Electrode were placed 2.5 cm anterior and 2.5 cm posterior to positions C3, C4, and Cz, of the “10-20 International System”, which is a standard for electrode placement based on the location of the cerebral cortical regions. The EEG was amplified between 0.5 and 30 Hz by an EEG amplifier (g.tec Guger Technologies, Graz, Austria) and processed in real-time. Sampling frequency was 250 Hz.

3.3 Feature Extraction and Classification

BCI systems apply an online classification to the EEG signal. Two frequency bands selected from each EEG channel served as features for the algorithm. The logarithmic band power was calculated in the alpha (8-12 Hz) and beta (16-24Hz) bands over one-second epochs. These features were classified with Fisher’s linear discriminant analysis (LDA) and transformed into a binary control signal.

3.4 The Virtual Environment

The study was carried out in a four-sided ReaCTor system that is similar to a Cave (Cruz-Neira et al., 1992), with Intersense IS900 head-tracking. The applications were implemented on top of the DIVE software (Frecon et al., 2001; Steed et al., 2001).

The environment included two furnished virtual rooms. The avatar was projected (using stereo display) to appear standing approximately half a meter in front of the subject, who was sitting on a chair. The avatars were matched for gender with the subject (see Figure 4).

(a)

(b)

Figure 4: (a) A female subject and her avatar in the virtual room. The subject is connected to the BCI equipment, inside the Cave-like system. (b) A male subject with the male avatar, in the same setting.

3.5 Experimental Conditions

The visual feedback was different in two conditions. In the first condition, which we call the *normal* condition, the mapping between the thought pattern and result in the IVE was intuitive: when the subjects imagined moving their right arm the avatar would wave its right arm, and when they imagined moving their legs the avatar would start walking forward slowly. In the second condition the mapping was reversed: when the subjects imagined moving their right arm the avatar would start walking, and when the subjects imagined moving their legs the avatar would wave its arm. The feedback was continuous for the same duration as in the monitor-based BCI training (4.25 seconds). In both conditions, the audio triggers were the same as in the training phase: single beep indicated that the subjects need to think about their arm, and a double beep indicated they need to think about their legs.

4 RESULTS

4.1 BCI Accuracy

Each subject carried out four runs of both conditions, thus eight runs in total. Each run included 40 trigger events, and each trigger was followed by 80 classification results, one every approximately 50 milliseconds. Thus, the data include 8 runs per subject, and each run includes 3200 trials. BCI accuracy is determined by the percentage of successful trials.

In order to test the significance of the results we carried out the equivalent of two-way analysis of variance, using the number of successes out of the 12800 trials in each of the conditions. In this analysis the response variable is therefore taken as a binomial distribution (rather than Gaussian) and it is a standard application of logistic regression. The results show that there were highly significant differences between the three subjects (at a significance level that is too small to be quoted). Subject M1 had the highest success rate (94%), subject F1 had the next highest (86%) and subject F2 the lowest (81%) – and these are in keeping with what is typically found in BCI experiments. The raw figures show that in the normal condition the success rate was 86.7% and in the reverse condition 87.7% and with n = 12800 per condition this difference is significant. However, this does not take into account the differences between the subjects – since the very large advantage of the reverse condition for subject F1 (88% reverse compared to 84% normal) distorts the overall result. For subject M1 the reverse condition is significantly higher than the normal condition (z = -11.3,P = 0) for subject F2 there is no significant difference between the reverse and normal condition (z = 1.02, P = 0.31) and for subject F1 the normal condition is significantly higher than the reverse condition (z = 3.88, P = 1.0e-4). These are carried out using a normal test for the difference between proportions. Thus, overall, no particular conclusion can be drawn one way or another about the effectiveness of the mapping in terms of BCI performance. Figure 5 depicts the performance of the three subjects in the two conditions.

4.2 Qualitative Results

The control of a virtual body using thought is a completely new type of experience, and we were interested in getting some insight into the subjective experiences of the subjects. We thus used a combination of questionnaires and semi-structured interviews. The goal of the subjective questionnaires and interviews is exploratory. We hope to partially reconstruct the subjective experience in order to gain insight into this novel experience; this is a type of ideographic study (Kelly and Main, 1978).

The subjective impressions of people, unlike their BCI accuracy, is dependent on contingent factors such as social background, video game exposure, etc. Below we describe what the three subjects reported, but a study with a larger number of subjects is necessary in order to extrapolate this evidence.

After their first IVE session, each subject completed several questionnaires: the SUS presence questionnaire (Slater et al., 1994), the Trinity questionnaire for body plasticity (TABP) (Desmond et al., 2002), and a questionnaire regarding body projection: When a person has the sensation that an object (whether real or virtual) is experienced as part of his/her own body, this is referred to as 'body projection'. The most famous example of this is the rubber arm illusion (Botvinick and Cohen, 1998; Armel and Ramachandran, 2003). In order to evaluate whether this type of body projection was experienced by our subjects, we have also administered a questionnaire recently designed in our lab for that purpose.

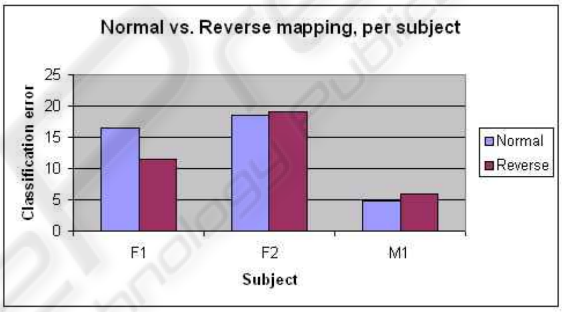

Figure 5: BCI error levels of the three subjects in the two experimental conditions.

The questionnaires are comprised of 7-point or 5-point Likert-scale questions. First, all questions were "normalized" so that all low and high rates indicate the same trend, e.g., low presence would always correspond to a low rating. Then we counted how many extreme (very low or very high) answers each subject provides (For 7-point questions 1 and 2 were considered low and 6 and 7 were considered high, and for 5-point questions only 1 and 5 were considered extreme). By subtracting the number of high scores from the number of low scores, we can classify the result of that questionnaire into three categories: low, high, or neutral. Our three subjects showed consistency in their answers – there was no case where there were both high and low scores for the same questionnaire. Table 1 summarizes the results, which were also used to complement the interviews in gaining an insight into the subject's experience.

After completing the questionnaires, the subjects went through a semi-structured interview. The interviews were audio-taped and transcribed. Such interview agendas are designed in advance to identify logically ordered themes, following the recommendations

Table 1: Summary of questionnaire results. Result in each category can be either high (+), low (-), or average (0).

Subject	Plasticity	Body projection	Presence
F1	+	+	0
M1	-	-	-
F2	-	0	+

of (Smith, 1977). We asked open-ended questions, and intervention was minimized to occasional neutral questions to encourage the subjects to continue.

4.2.1 IVE-BCI versus “Traditional” BCI

All subjects found the IVE-based BCI to be more enjoyable and interesting. This is obvious, but may be important in its own right: BCI training is typically very long and exhausting; IVE may prove useful in significantly improving the training experience and increase motivation.

Subjects F1 and F2 thought the IVE-based BCI was easier (although they did not actually improve their BCI performance). Subject F1 compared the monitor-based BCI (which she refers to as a ‘little line’) with the IVE experience: “I felt it was easier to make her do things. Because something was actually happening. Because when you’re thinking about your feet but it’s just a little line whereas if you’re thinking about your feet and she moves it’s, I don’t why, it just seemed make to more sense.” Subject M1, who reported very low presence, mentioned the IVE was more enjoyable.

4.2.2 Relationship with Avatar

Note that the subjects were not told that the virtual body is intended to be their avatar, and in principle there is no reason why people should associate this virtual body with themselves. However, two of the three subjects (M1 and F2) referred to the virtual body as a puppet controlled by them, which is a typical way to regard an avatar. The third subject (F1) even occasionally referred to it in first person.

Subject F1 seemed to have the highest level of projection of her body to the avatar. This was not only evident from the questionnaire, but also, during the sessions. At first, the subject referred to the avatar as “she”, but after a few runs she started referring to it as “I”. In the questionnaires this subject reported a medium level of presence, and a high degree of body plasticity. In the interview, this subject said: “Although I was controlling her, I wasn’t moving my hand. and I’d know if I was moving my hand.” However, later she added: “..Oh yeah. It’s because I, my brain, did move the hand. Towards the end I did feel it was representing me. I always felt like it was representing me but I didn’t feel it was a part of me... It’s difficult. When you think about moving your hands you know whether you’re moving your hands or not. If she was moving her hand mine wasn’t moving. So she can’t really be a part of me. -Cause to feel the hand moving you’d have to feel the air going past it. But the more you were in the more comfortable you would become with that becoming you. It would just be a different type of you. Like a different version of you, almost. But it will never be you... First like another body. Most of the time.”

Subject F2 reported higher presence but lower levels of body plasticity and body projection. “I couldn’t think of her as myself. I was trying to get into her skin, it was frustrating when I couldn’t.. when i was successful I was becoming closer, I was becoming her. Or she was becoming me. I’m still saying that for me to experience my movement somehow she was a distraction. Thinking of movement I could have done better without her. We didn’t click...But the connection was more like a puppet master...Get rid of her. Just let me move in the environment - that was amazing. She was the task I was supposed to do.”

Subject M1 reported low presence and low body projection. In the interview, he said: “First I thought it was another person standing in front of me. I thought what the objective was. I was wondering what would happen to this person. I didn’t feel as it being my body but I felt I had some control of the person or of the body standing in front of me... I would best describe it like a puppet.”

4.2.3 Mapping of Thoughts to Avatar Motion

Note that although we consider the mapping between thought patterns and resulting avatar action to be natural in the normal condition, the mapping is not necessarily perfect. For example, subjects were not instructed to think of a particular leg motion, and thus they imagined cycling or kicking, whereas the avatar, although it moved its feet, would perform a different action: walking. This could be confusing for the subjects, and might even divert them from the specific thought they have been trained with. In the interviews, all subjects replied that this mismatch was not a problem, and that the feedback seemed appropriate. We do not know if this mismatch affects the BCI performance.

Subjects F1 and F2 (who experienced medium and high presence, respectively) mentioned that the fact that they were sitting and the avatar was standing was more problematic. F2: “I usually do not walk forward while I am sitting down..” We, of course, anticipated this problem. In pilot runs we tried to have the subject stand in the Cave; this proved uncomfortable and generated too many motion artifacts in the EEG signals. We could have had the avatar sit down, but that was not the point of the study; in our vision for a future you project your body onto the avatar's body, and then the avatar can be free to operate in the VE, controlled by your thought.

When asked about the difference between the two conditions, all subjects mentioned that they had to concentrate more in the reverse condition. This may be an explanation as to why they sometimes performed better in the reverse condition than in the normal condition. F1: "It was confusing, but I didn't find it difficult." F2: "I'm not sure if seeing the feedback was so confusing – just adding all these layers. It made it difficult to concentrate." M1 reported very low presence, yet mentioned: "I was surprised that when it was reversed I found it harder to concentrate. It made me confused. At all times, not only in the beginning. So there must have been something on another level – I must have been influenced."

5 CONCLUSION

We have devised a system that allows people to be able to control a virtual body in an IVE, with accuracy ranging from 72% to 96%. We consider this to be a proof of the feasibility of this innovative interface. We have used qualitative methods to get a sense of this new type of experience: what did it feel like? what was the nature of the relationship between the subjects and their avatars?

There is growing interest in the BCI community to use IVE, and some evidence that IVE may assist in BCI training, or even improve BCI performance. Our finding suggests that BCI in IVE is more enjoyable than traditional BCI, and subjects find it more intuitive and natural. However, subjects did not seem to perform better when the mapping between their thoughts and the feedback was natural, as compared to when this mapping was reversed. This is despite the fact that the subjects did report that the reverse condition seemed more confusing and less intuitive. The results we describe in this paper thus indicate that the story is complex and justify further research.

In 1965 Sutherland described the Ultimate Display system – which was the forebear of today's highly immersive virtual reality systems (Sutherland, 1965). In this paper we are pointing the way towards the Ultimate Human-Computer Interface, an interface through thought - as has been described in novels by authors such as William Gibson (Gibson, 1984) and Neal Stephenson (Stephenson, 1991). The research described in this paper has shown that it is possible to control a virtual body by thought, and has explored performance-related results and the subjective experience that this entails. In future work we plan to take this paradigm further, by trying to achieve a higher level of body projection from participants to their avatars, and by allowing the participants to achieve a larger variety of tasks through their avatars, which they control by thought. We hope this could be a first step towards an ultimate future interface.

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