

Avatar navigation in virtual and augmented reality environments using an SSVEP BCI

ICABB-2010

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Abstract—This work reviews steady-state visual evoked potential (SSVEP) brain-computer interface (BCI) systems that integrate stimuli within desktop-based virtual reality (VR) and augmented reality (AR) environments. SSVEPs are brain signals that allow for high information transfer rates (ITR) within BCI systems while requiring only minimal training. Generating SSVEP stimuli within 3D computer graphics makes it easier to implement motivating training paradigms and more realistic simulations of real-world applications. Electroencephalogram (EEG) measurements on seven healthy subjects within three VR scenarios and on three healthy subjects within an AR scenario showed that software generated stimuli are suitable to elicit SSVEPs. This research direction could lead to vastly improved immersive VEs that allow both disabled and healthy users to seamlessly communicate or interact through an intuitive, natural, and friendly interface.

Keywords: Electroencephalography (EEG), Brain-Computer Interface (BCI), Virtual reality (VR), Augmented Reality (AR), Bionics.

I. INTRODUCTION

Brain-computer interface (BCI) systems (see Vidal, 1973; Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002; Pfurtscheller et al., 2006) establish a channel of communication and/or control between a human brain and a computer. They determine user intention, based upon classification of characteristic temporal, spatial or phase patterns within the brain. The electroencephalogram (EEG) BCI systems presented in this work rely on the fact that visually focusing on a flickering light elicits steady-state visual evoked potentials (SSVEPs) that can be isolated and identified from the EEG over the occipital cortex. SSVEP BCIs are classified as exogenous BCIs, since an external stimulus is required to produce the necessary brain activity. Although most of the SSVEP BCI systems (including this one) are dependent (depend on muscular activity, e.g., gaze shifting), Allison et al. (2008) proved that this is not an

inherent necessity. The feedback presented in these studies (Faller et al. 2010a; Faller et al. 2010b) is based on the mixed reality framework Studierstube (Schmalstieg et al., 2002). Virtual and augmented reality (VR and AR respectively) environments have proven to be very motivating and can provide an intuitive, natural and friendly interface for both disabled and healthy users to seamlessly communicate and/or interact with a computer and/or their environment. This may lead to higher user acceptance for entertainment, control or rehabilitation systems. More immersive feedback environments could prove especially useful for simulating SSVEP BCI use in real world situations that would otherwise require exposing the user (probably a patient) to discomfort or danger (e.g., training for SSVEP operation of a wheelchair).

II. RELATED WORK

In Lalor et al. (2005), subjects had to operate a two-class software SSVEP game (a 3D character balancing on a bar) using a fixed checkerboard pattern stimulus. Martinez, Bakardjin, and Andrzej (2007) used a four-class software SSVEP BCI with a moving checkerboard stimulus to steer a car from a bird's-eye view. Work presented in Leeb (2008) describes the impact of VR feedback on the performance and motivation of subjects within event-related desynchronization (ERD) BCIs. Further work that presents VR feedback for BCI systems includes Lotte et al. (2010) and Bayliss (2003). Some previous studies investigated the feasibility of software-generated stimuli in SSVEP BCIs. However, in none of the cases were the stimuli implemented as actual 3D objects within the scene but rather as 2D objects superimposed on the game scenes. This work presents a reusable implementation of real 3D SSVEP stimuli that can be more realistically embedded within 3D graphic scenes.

III. METHODS

A. Subjects and Signal Acquisition:

In the work presented, seven subjects participated in the first and three in the second study. Signals were derived in a bipolar setup at O1 and O2 according to the 10–20 system (Jasper, 1958). The signal was sampled at 256 Hz, notch-filtered at 50 Hz and band-filtered between 0.5 and 100 Hz. For real-time processing, rtsBCI (Schlögl & Brunner, 2008) along with the Harmonic Sum Decision (HSD) method presented in Müller-Putz et al. (2005) were used.

Manuscript received July 28th, 2010. This work was supported in part by the FP7 EU research projects PRESENCCIA, IST-2006-27731 and BRAINABLE, ICT-2009-247447.

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B. Experimental Setup and the Scenarios:

The subjects were seated in a comfortable leather armchair 105 cm away from a 17 inch Eizo FlexScan L565 TFT monitor (Eizo Nanao Corporation, Matto, Japan) operated at a refresh rate of 60 Hz in the first scenario. The immersive AR scenario was set up via a head-mounted display, a head-mounted camera and fiducial marker tracking. All paradigms were completely self-paced.

C. Classification:

The classification system is based upon HSD and continuously analyzes the EEG. It adds up the power density amplitudes of the first, second, and third harmonic individually for each of the target frequencies. For one class to be selected, the sum of all its harmonic frequency components needs to be larger than that of the other classes all through a dwell time of 1.5 s. A refractory period of 4 s follows each successful classification, which allows for a theoretical maximum of 10.9 activations per minute. The amplitudes were normalized by reference values recorded once at the beginning of the session.

D. Button Scenario:

The camera shows the first person perspective of an avatar facing down at his feet (see Fig. 1). The two quadratic SSVEP target stimuli in the Button scenario were placed directly next to the hands of the avatar. The task is to achieve as many correct activations as possible over a fixed time interval. The paradigm requires the alternating achievement of three correct activations for each of the two classes starting with the left (e.g., L-L-L, R-R-R, L-L-L, etc.). Every correct activation triggers the corresponding button press animation. Each activation that corresponds to the predetermined pattern is counted as TP, and any other activations are counted as FP. The left and right SSVEP lights were flickering at 12 and 15 Hz, respectively.

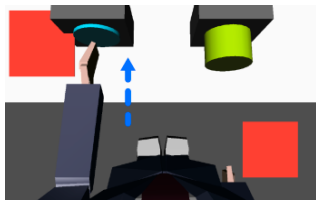


Fig. 1. Button scenario

E. Slalom Scenario:

Both the Slalom (see Fig. 2) and Apartment scenarios (section E) offer three quadratic SSVEP target stimuli surrounding the avatar. They allow for the following movement commands from left to right: (i) turn 45° left, (ii) walk one unit straight ahead, and (iii) turn 45° right. For the left, top, and right SSVEP stimuli in both the Slalom and Apartment scenarios, the frequencies 12, 20, and 15 Hz were used. The camera follows the avatar in a fixed-angle, third person perspective. The task was to walk the avatar through

the slalom following the predetermined path in less than 10 min. The main performance measure was the time to finish along with the number of TP and FP activations per minute.

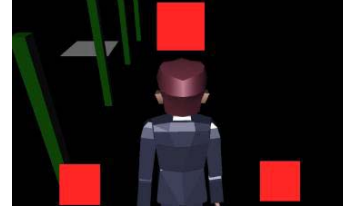


Fig. 2. Slalom scenario

F. Apartment Scenario:

The main difference in the Apartment scenario (see Fig. 3; based upon work published in Leeb et al., 2007) compared to the previous experiment is the complexity of the background. Two runs were recorded with this scenario. In the first run, the subject had to navigate the avatar to the first way-point in the middle of the apartment; in the second run, the subject had to reach the second way-point at the diagonally other side of the apartment. The main performance evaluation criteria were the number of TP and FP per minute along with whether or not the subjects were able to reach the respective targets (target 1 within the first run; target 2 in the second run) in the upper time limit of 10 min.



Fig. 3. Apartment scenario

G. Augmented Reality Slalom:

We implemented an SSVEP BCI based on four target stimuli integrated in an asynchronous AR SSVEP BCI setup (see Fig. 4 and 5), three for navigation attached to the avatar and one statically placed at the top right screen corner for switching the other stimuli on and off. The task was to navigate the avatar through a slalom scenario, while holding for 30 second stops at platforms placed at the beginning and end of the slalom.

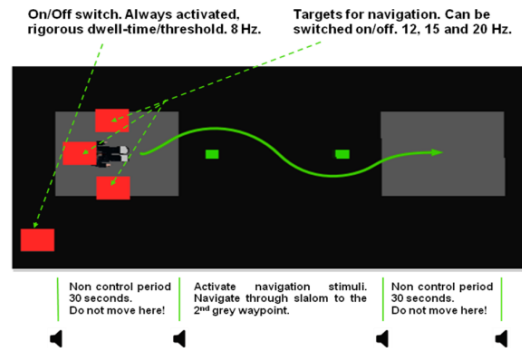


Fig. 4. Description of AR scenario paradigm

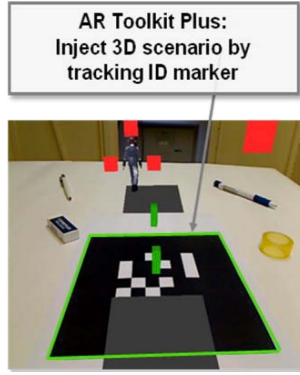


Fig. 5. AR scenario

H. Performance Evaluation:

Depending on the scenario, different criteria were used to evaluate subject performance. These include the number of (i) true positive (TP; intentional) and (ii) false positive (FP; unintentional) activations, both per run and per minute, but also (iii) positive predictive value (PPV; also called precision; see Altman and Bland, 1994; $TP/(TP+FP)$), (iv) time to finish, and (v) whether or not the subject was able to finish the task within the given time frame.

IV. RESULTS

A. Button Scenario:

Table I shows the results for the Button scenario. The results suggest that at least for five out of the seven subjects, the refractory period could have been a limiting factor keeping them from achieving more correct activations per minute. These subjects achieved between 8.8 and 10.1 activations per minute. This comes close to the theoretical maximum of 10.9 activations per minute mentioned before.

TABLE I
RESULTS FOR BUTTON SCENARIO

Subject	PPV (%)	TP (min^{-1})	FP (min^{-1})
AT7	83.3	5.6	1.1
Z24	91.4	6.6	0.6
AQ9	100.0	8.8	0.0
AU4	98.6	8.9	0.1
T4	97.4	9.5	0.3
AV1	98.8	10.0	0.1
AO3	98.8	10.1	0.1
Mean	95.5	8.5	0.3
SD	6.1	1.7	0.4

B. Slalom Scenario:

Table II gives a detailed overview of the results. It is sorted ascending by TP activations per minute.

TABLE II
RESULTS FOR SLALOM SCENARIO

Subject	PPV (%)	TP (min^{-1})	FP (min^{-1})	ϕ Time (s)
Z24	85.7	4.5	0.80	291
AT7	98.6	6.0	0.09	228
AQ9	98.2	6.8	0.12	164
AV1	91.0	7.1	0.71	170
AO3	92.9	8.3	0.65	124
T4	98.2	8.4	0.16	129
AU4	98.3	8.6	0.15	135
Mean	94.7	7.1	0.37	177
SD	5.0	1.5	0.31	62

C. Apartment Scenario:

Table III shows an overview of the results for all subjects, sorted by the conditions Run 1/Run 2 successful and then by the TP activations per minute.

TABLE III
RESULTS FOR APARTMENT SCENARIO

Subject	PPV (%)	TP (min^{-1})	FP (min^{-1})	Run 1	Run 2
AT7	78.3	3.8	1.0	no	no
Z24	76.7	3.2	1.1	yes	no
AQ9	96.7	6.5	0.2	yes	yes
T4	96.7	6.5	0.2	yes	yes
AV1	95.2	6.7	0.3	yes	yes
AU4	100.0	8.3	0.0	yes	yes
AO3	98.6	9.4	0.1	yes	yes
Mean	91.7	6.5	0.4		
SD	9.9	2.3	0.4		

D. Augmented Reality Slalom:

Within this pilot study, two out of three subjects successfully managed to complete the AR scenario within the given time limit.

V. DISCUSSION

All subjects were able to control the self-paced VR scenarios using an SSVEP based BCI. The first VR scenario (an avatar pressing two different buttons) was controlled via two SSVEP stimuli. In the second and third scenarios, the subject had to navigate an avatar through a Slalom and an Apartment scenario with three SSVEP stimuli. The average positive predictive value (PPV) over all three scenarios was above 93%, which indicates that the BCI system is effective in correctly recognizing user intention. Still, the average PPV gradually decreases over the three scenarios from 95.5 over 94.7 to 91.7%. The average number of TP activations per minute for the three scenarios were 8.5 over 7.1 to 6.5. However, factors other than speed may be more important to the user. For instance, choosing a higher refractory period makes the SSVEP BCI easier to use (and also useable out of

the box for a larger number of people), less fatiguing, and more reliable. The AR pilot study shows that SSVEP BCIs can be operated with target stimuli that are tightly integrated within highly dynamic and complex AR setups. Both SSVEP BCI feedback types allow for interesting and useful applications including entertainment (e.g. games, second life for disabled people) and rehabilitation (e.g. virtual limbs, realistic simulation of SSVEP wheel-chair operation). The AR setup shows great potential to become a very useful communication and/or control interface within home, office or other more specialized work environments (e.g. BCI in space). Used in context of more sophisticated ubiquitous environments, AR SSVEP BCIs could adjust placement and function of presented stimuli dynamically to the current view of the user or the status of the environment.

VI. CONCLUSION

Future research should strive to further improve the accuracy of software SSVEP stimuli to approach the quality of LED stimulation, particularly within more complex 3D scenarios. For the VR scenarios it would be interesting to further investigate how technologies like stereo walls or cave automated virtual environments (CAVEs) affect subject performance and/or motivation. The integration of the software SSVEP BCI system with an augmented reality environment is one step toward making this technology applicable in other fields as in home or office use for both patients and healthy users. Another idea would be to implement additional brain signals extending this system to a hybrid BCI. Possible advantages might include an extended number of available classes, an increase in accuracy or a higher stability.

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