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An Application Framework for Controlling an Avatar in a Desktop-Based Virtual Environment via a Software SSVEP Brain–Computer Interface

Abstract

This paper presents a reusable, highly configurable application framework that seamlessly integrates SSVEP stimuli within a desktop-based virtual environment (VE) on standard PC equipment. Steady-state visual evoked potentials (SSVEPs) are brain signals that offer excellent information transfer rates (ITR) within brain–computer interface (BCI) systems while requiring only minimal training. Generating SSVEP stimuli in a VE allows for an easier implementation of motivating training paradigms and more realistic simulations of real-world applications. EEG measurements on seven healthy subjects within three scenarios (Button, Slalom, and Apartment) showed that moving and static software generated SSVEP stimuli flickering at frequencies of up to 29 Hz proved 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.

1 Introduction

Brain–computer interface 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 spatial and/or temporal activation patterns within the brain. The BCI system presented in this paper relies on the fact that visually focusing on a flickering light elicits steady-state visual evoked potentials (SSVEPs) that can be isolated and identified from an electroencephalogram (EEG) of 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 this paper is based on the virtual reality (VR) framework Studierstube (Schmalstieg et al., 2002). Virtual environments (VE)

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have proven to offer very friendly, motivating, and safe feedback within BCI experiments. A virtual humanoid character was used in the experimental paradigms, since that accounts for more intuitive and motivating feedback. Being able to directly integrate SSVEP stimuli as actual 3D objects within VEs allows for the implementation of very interesting, realistic, and game-like 3D feedback scenarios. SSVEP scenarios that are implemented in this way are likely to be more motivating for both healthy and disabled users, which leads to higher user acceptance. The stimuli can be used to implement 3D scenarios for entertainment or rehabilitation, or to integrate assistive systems for healthy and disabled people. This software SSVEP system can also be extended to work within highly immersive virtual, augmented, or mixed reality environments. Those 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). The goal of this particular contribution is to implement a flexible, configurable, and reusable VR framework that supports the control of 3D avatars based on SSVEP.

2 Related Work

A 12-class software SSVEP BCI with comparably high transfer rates was presented in Cheng, X. Gao, S. Gao, and Xu (2002). 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) described the impact of VR feedback on the performance and motivation of subjects within event-related desynchronization (ERD) BCIs. Some previous studies addressed the implementation of software 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.

3 Methods

3.1 Architecture of the System

Figure 1 shows the architecture overview diagram for the complete SSVEP BCI system. The signal acquisition block consists of electrodes and a biosignal amplifier as described in Section 3.2.1. The data acquisition (DAQ) card in the dedicated BCI PC performs A/D conversion on the analog signal from the amplifier and allows the MATLAB Simulink real-time SSVEP BCI application that is based upon rtsBCI (Schlögl & Brunner, 2008) to access the EEG signal. This application determines which SSVEP target stimulus the subject is focusing on by applying the methods described in Section 3.2.4 on the ongoing EEG signal. The SSVEP BCI application continuously sends control commands via the network to the feedback application which is running on a dedicated PC.

The 3D feedback application is built upon the VR framework Studierstube (Schmalstieg et al., 2002). One of the central parts of the feedback application is the command relay application (StbBCICommApp), which is based upon work presented in Poric (2008). It evaluates and executes the incoming control commands (e.g., retrieve a reference to an avatar instance and start a movement). The other important components, SoSSVEP and SoSSVEPAvatar, are implemented as Open Inventor custom nodes. SoSSVEP is used to display SSVEP stimuli. SoSSVEPAvatar allows for the integration of virtual characters based upon the PIAVCA (platform independent API for virtual characters and avatars; Gillies, Vinayagamoorthy, Robertson, & Steed, 2005) library.

3.2 EEG Measurements

3.2.1 Subjects and Signal Acquisition. Seven healthy adults, 24 to 31 years old (5 male, 2 female;

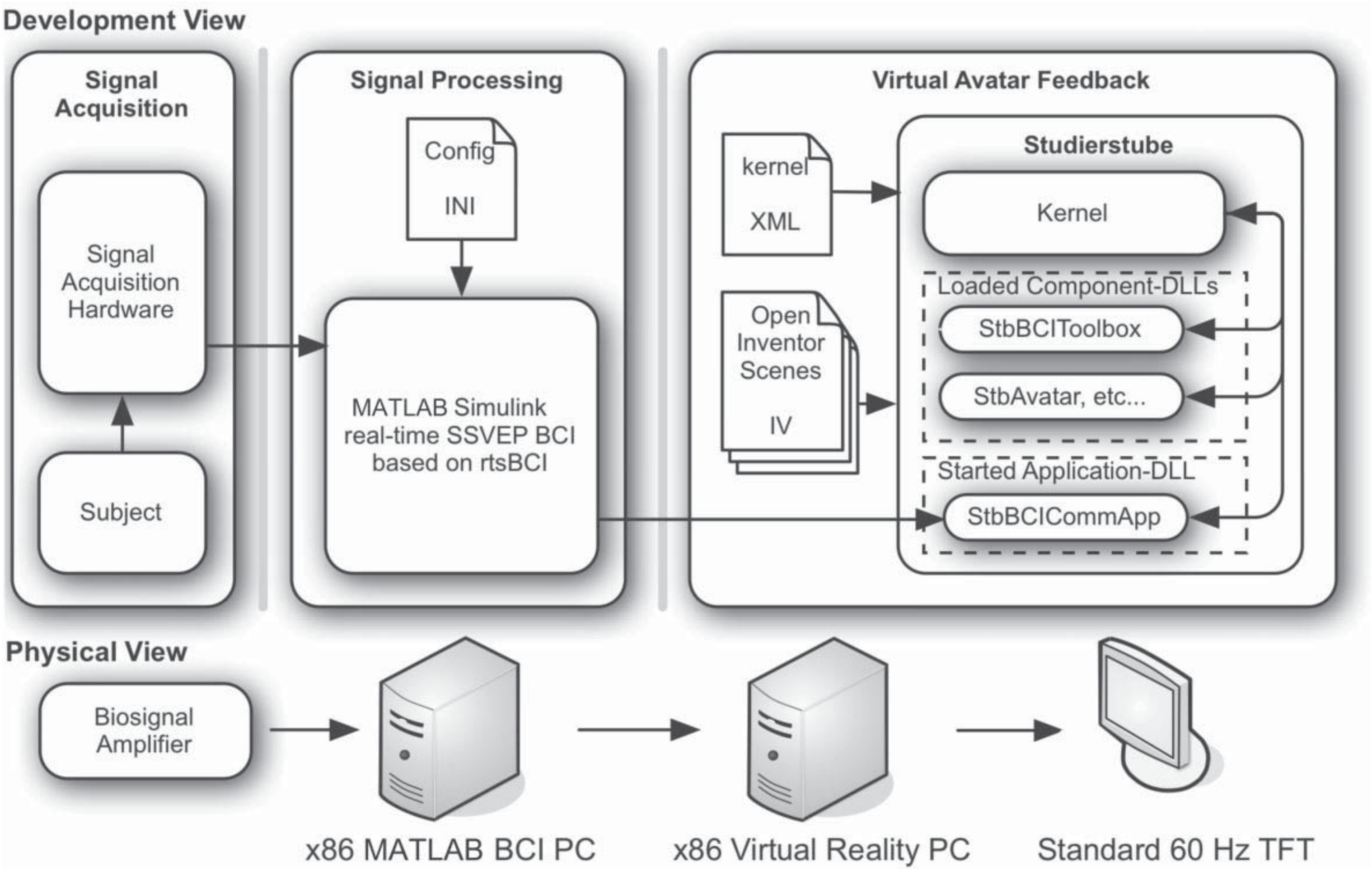

Figure 1. *Architecture overview diagram for the whole BCI system.*

mean 26.3 ± 3.4), with normal or corrected to normal vision voluntarily participated in the studies. All of them had at least some experience in using SSVEP BCI systems. The purpose and detailed characteristics of the measurements were explained beforehand in written form. In the rest of this paper, a complete measurement for one subject on one day will be referred to as a session and an actual record from start to end of a single measurement in one particular paradigm will be called a run. The three presented scenarios, Button, Slalom, and Apartment, were recorded in that order during one session. All data recorded is presented in this paper. Signals were derived according to the 10–20 system (Jasper, 1958) using five sintered Ag/AgCl electrodes in a bipolar setup, 2.5 cm anterior and posterior to O1 and O2 with ground placed at Fpz. All impedances were kept below 5 kΩ. Data acquisition was handled through a biosignal amplifier (g.tec, Guger Technologies, Graz, Austria), a data acquisition card (NI-6031E, National Instruments Corporation, Austin, Texas), and a standard x86 PC running Windows XP (Microsoft Corporation, Redmond, Washington). The signal was band-filtered between 0.5 and 100 Hz. A notch filter was applied at 50 Hz. The signal was sampled at $f_S = 256$ Hz and stored in GDF v2.0 file format (Schlögl, 2006). For real-time processing, rtsBCI (Schlögl & Brunner, 2008) along with the Harmonic Sum Decision (HSD) method presented in Müller-Putz, Scherer, Brauneis, and Pfurtscheller (2005) were used.

3.2.2 Performance Evaluation.

The offline evaluations were carried out under the assumption that the subjects fully understood and strictly obeyed the specific instructions for each task. 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, and Equation 1 for the definition), (iv) time to finish, and (v) whether or not the subject was able to finish the task within the given time frame.

$$\mathrm{PPV} = \frac{\text{True Positive Activations}}{\text{True Positive Activations} + \text{False Positive Activations}} \tag{1}$$

3.2.3 Experimental Setup and the VE Scenarios.

All measurements were conducted inside a shielded room. 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). The response time of this monitor is 30 ms. It was operated at a resolution of 1024 × 768 pixels and a refresh rate of 60 Hz. Figures 2, 3, and 4 show screenshots of (i) the Button, (ii) the Slalom, and (iii) the Apartment scenarios. The initial ranges for the configuration parameters were set based on related work from Cheng et al. (2002), Lalor et al. (2005), and Kroneis (2008). The parameters were fixed after pilot studies within multi-condition measurements on a group of five subjects as described in Faller (2009). When testing icosahedron, triangular, and rectangular stimulus shapes, the rectangular shape proved most effective in eliciting SSVEPs. All SSVEP stimulus presentation was implemented in the field-configurable Open Inventor custom node SoSSVEP. In the presented scenarios, the stimuli were configured to steadily flicker (hard switch) between the colors red (RGB = 1, 0, 0) and black (RGB = 0, 0, 0) while leaving other parameters unchanged. That setup yielded a better response than the formerly tested white/black variant. The flickering accuracy was measured using a phototransistor circuit and optimized by programmatically ordering Studierstube to render the SSVEP stimuli at the maximum possible rate. VSync was disabled because tests showed that it decreased flickering accuracy.

The gray coloring of the target stimuli in the screen shots is actually just for exposition. Within one particular frame during a real measurement, each of these stimuli might be colored either red or black depending on stimulus frequency and time. The actual on-screen sizes of the quadratic SSVEP target stimuli can be seen in Figures 2, 3, and 4. Quadratic stimuli with edge lengths of as small as 2 cm over a distance of 105 cm were shown to work in the presented setup. Also, vertically moving the stimulus during the measurement did not

Figure 2. *The target stimuli are placed next to the avatar hands. The left picture shows the starting position. A first correct activation of the left target stimuli would trigger the avatar to lift the left hand. The right picture shows the second correct activation of the left target stimuli, which makes the avatar push the button. A third correct activation would trigger the left arm to go down again.*

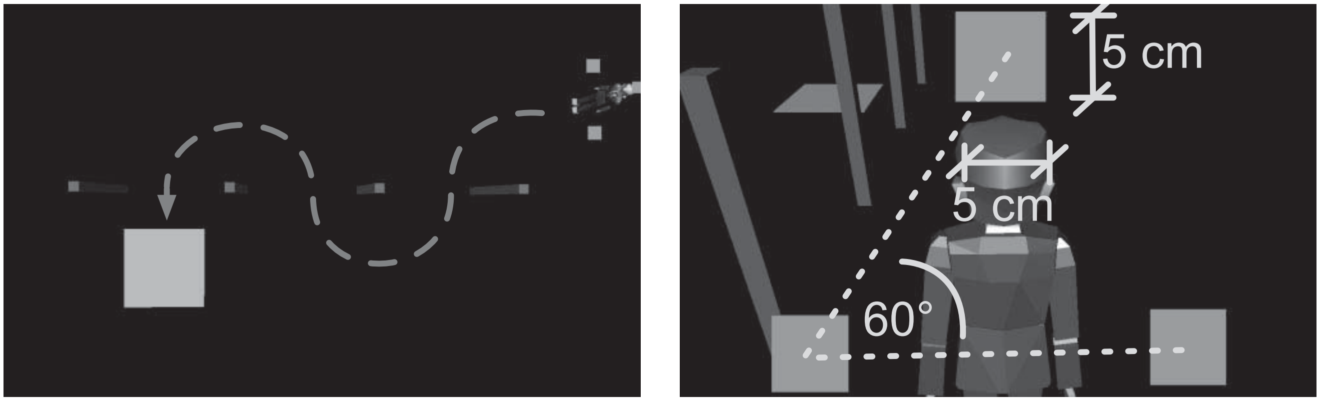

Figure 3. *The dashed line in the left picture shows the predetermined path through the slalom, while the right picture shows an actual in-measurement screenshot of the avatar in the starting position. The right picture also describes sizes and alignment of the stimuli.*

adversely affect the classification results. The same frequencies were used for all subjects. See the scenario descriptions for the exact values. The radiation intensity over the SSVEP stimuli was 12 μW/cm^2. All paradigms were completely self-paced, and therefore neither provided cues nor obeyed a given timing.

3.2.3.1 Button Scenario. The camera shows the first person perspective of the avatar facing down at the avatar's feet. The two quadratic SSVEP target stimuli in the Button scenario were placed directly next to the hands of the avatar. They are configured to follow the movements of the avatar. The task is to achieve as many correct activations as possible over a fixed time interval of 4 min. 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 on one side triggers the corresponding part of the button press animation. Figure 2 describes the three stages. Each activation that corresponds to the predetermined pattern is counted as TP, and any other activations are counted as FP. In order to avoid any loss of subject motivation, there is no feedback for FP activations. Two runs of this

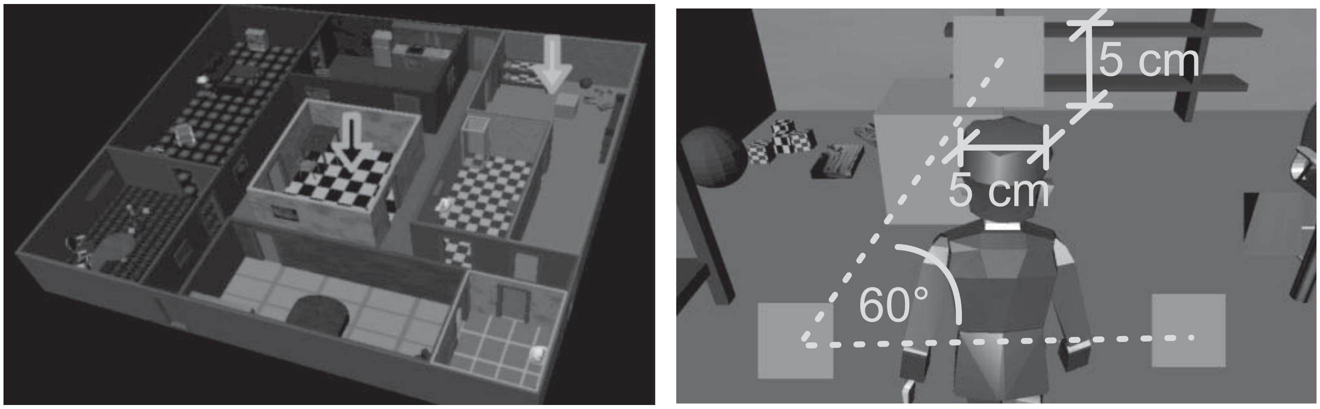

Figure 4. *The left screenshot shows an isometric view of the apartment with first and second target (black and gray arrow, respectively), whereas the right picture shows the avatar standing a few steps away from the second target. The right picture also describes sizes and alignment of the stimuli.*

paradigm were recorded during one session. One run lasted 4 min, resulting in 8 min of data for this scenario. The left and right SSVEP lights were flickering at 12 and 15 Hz, respectively.

3.2.3.2 Slalom Scenario. Both the Slalom and Apartment scenarios 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 (see Figure 3) following the predetermined path in less than 10 min. Three runs of this paradigm were recorded. The main performance measure was the time to finish along with the number of TP and FP activations per minute. Every single turn that had to be corrected in the opposite direction in order to stay walking along the path was counted as an FP. Corrections were counted as TPs. Interviews after each run helped to reveal any remaining unintentional activations.

3.2.3.3 Apartment Scenario. Control in the Apartment scenario works exactly the same as in the Slalom scenario. The main difference in the Apartment scenario (see Figure 4, based upon work published in Leeb et al., 2007) is the complexity of the background. Two runs of this scenario were recorded. Figure 4 also shows the two waypoints in the Apartment scenario. In the first run, the subject had to navigate the avatar on the fastest possible way to the first waypoint; in the second run, the subject had to additionally reach the second waypoint. 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; targets 1 and 2 in the second run) in the upper time limit of 10 min.

3.2.4 Classification. The system is based upon HSD and continuously analyzes the EEG. It calculates the zero-padded 1024-point FFT in every sample using a window length of 1.5 s, then 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 response at distinct frequencies is naturally different; therefore amplitudes were normalized by reference values recorded once at the beginning of the session. There were two such baseline recordings, one in the Button scenario and one within the Slalom scenario, each lasting 1 min. During this time, all stimuli were flickering with the same frequencies as during the actual measurements. The subjects were instructed to focus on a reference spot in the middle of the bottom frame of the TFT monitor for the whole minute. The reference values from the Slalom scenario were also used for the Apartment scenario.

4 Results

4.1 Implementation of the Virtual Feedback

SSVEP stimulus presentation is implemented in the reusable Open Inventor custom nodes SoSSVEP of the component StbBCIToolbox. Both moving and static rectangular non-VSync software SSVEP stimuli of more than 4 cm^2 in size, flickering between red and black at frequencies up to 29 Hz, proved suitable to elicit steady-state visually evoked potentials on a standard 60 Hz TFT monitor. The functionality to add highly configurable, remotely controllable avatars, is integrated in the custom node SoSSVEPAvatar of the component StbBCICommApp. All these packages can be easily integrated in Studierstube or every other Open Inventor compatible framework.

4.2 Evaluation of the EEG Measurements

4.2.1 Button Scenario. Table 1 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 activations per minute. These subjects achieved between 8.8 and 10.1 activations per minute. This is comparable to the theoretical maximum of 10.9 activations per minute mentioned in Section 3.2.4.

Table 1. *Results for the Button Scenario in Order of Ascending TP[min^{-1}]*

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

4.2.2 Slalom Scenario. Figure 5 shows the slalom paths for three different subjects (AU4, AT7, and Z24). The rectangle represents the target area and the points mark the positions of the slalom poles. Table 2 gives a more detailed overview of the results.

4.2.3 Apartment Scenario. Figure 6 shows the runs through the Apartment scenario for subject AV1, who performed third best in this category. Table 3 shows an overview of the results for all subjects.

5 Discussion

Apart from P300 (Bayliss, 2003) and the dynamics of sensorimotor rhythms (event-related synchronization/desynchronization, ERS/ERD; see Pfurtscheller and Lopes da Silva, 1999; Pfurtscheller et al., 2006; Leeb et al., 2007) SSVEPs can also be used to control VR applications (e.g., Lalor et al., 2005). This paper presents a flexible, reusable framework that supports the control of avatars within virtual scenarios using a software SSVEP BCI. All seven subjects were able to control the system after minimal training. There were three self-paced SSVEP scenarios. The first scenario involved an avatar pressing two different buttons and was controlled via two SSVEP

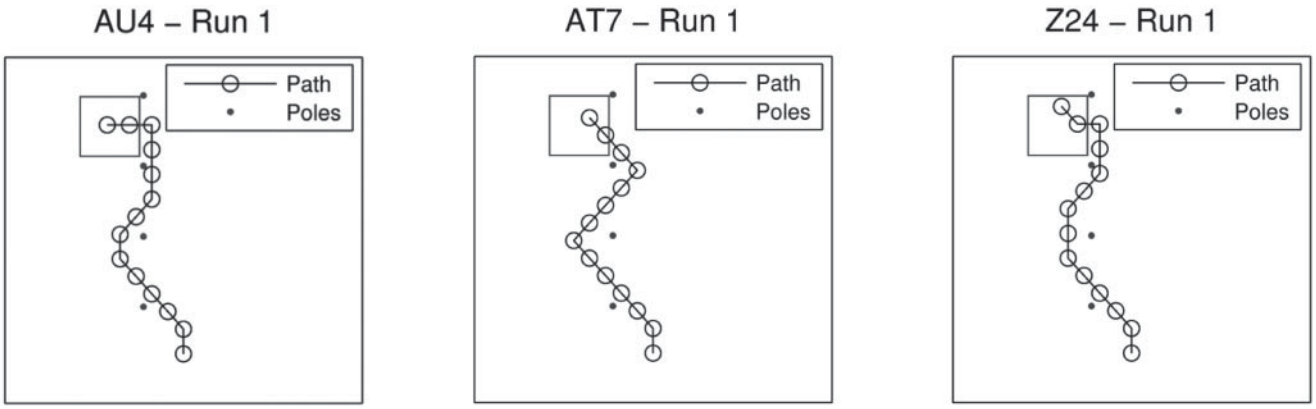

Figure 5. *Slalom path results for the three subjects AU4, AT7, and Z24.*

Table 2. *Results for the Slalom Scenario in Order of Increasing TP[min^{-1}]; Time in Seconds Reflects the Average Time to Finish Over All Three Runs*

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

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 very 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 decrement from the Button to the Slalom scenario is most likely caused by the complexity introduced with the additional SSVEP target and the more demanding task. The much larger deterioration in the PPV from the Slalom to the Apartment scenario can be explained by the even more complex task (navigating through the Apartment) and the colorful (nonblack) environment which has been shown to negatively affect the flickering accuracy of the target stimuli (tested within pilot studies with a phototransistor circuit). Given a dwell time of 1.5 s and a refractory period of 4 s, the average number of TP (min^{-1}) for the three scenarios were 8.5 over 7.1 to 6.5. Results of a follow-up measurement on subject AQ9 within the Button scenario showed that reducing the dwell time (down to 1 s) and refractory period (down to 1 s) allowed for an increase in TP (min^{-1}) from 8.8 up to 20. Unfortunately, the PPV also decreased from 100 to 90.9%, which indicates that it was more difficult for the subject to operate the BCI. 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.

6 Conclusion and Future Perspective

The developed desktop based virtual environment proved effective in producing visual stimuli that were capable of eliciting steady-state visual evoked

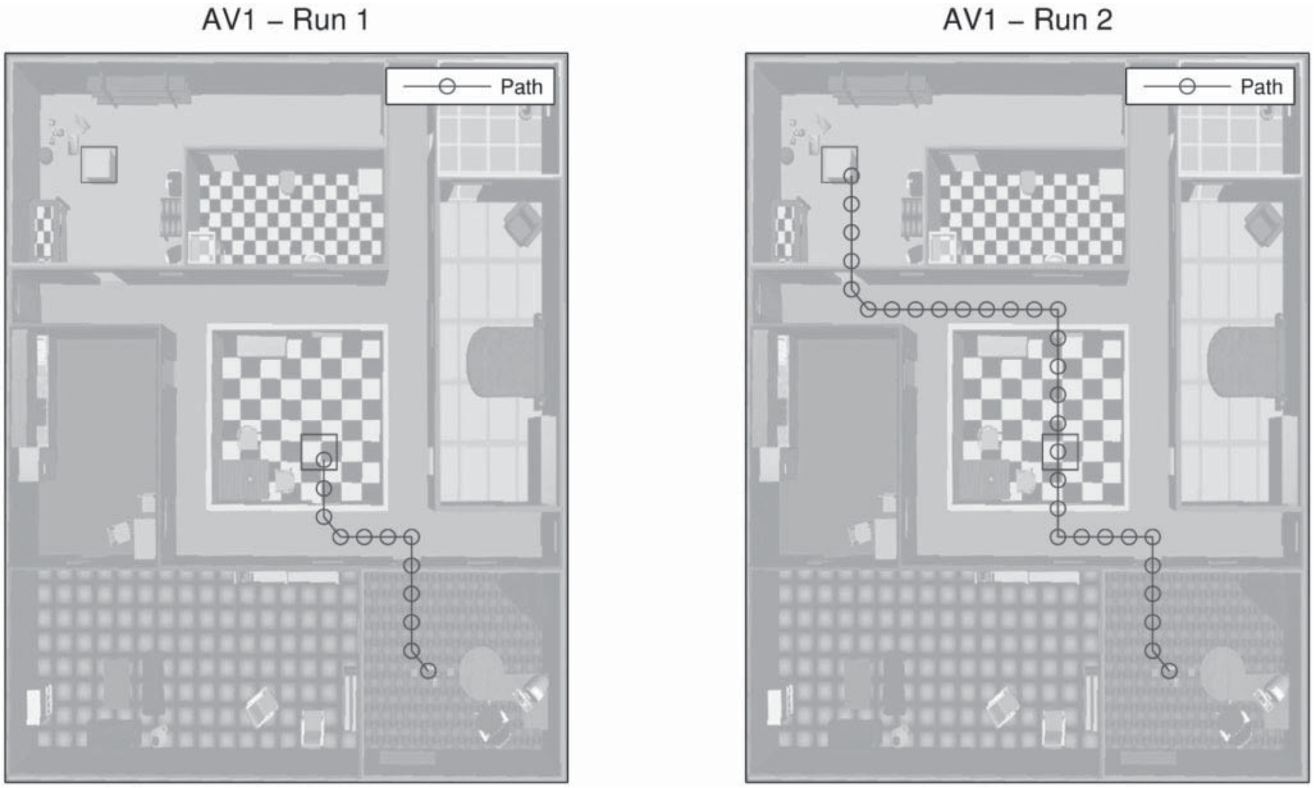

Figure 6. *Result paths through the Apartment scenario for AV1. The two pictures show the two runs with the respective target waypoints 1 and 2 for the left and right picture, respectively.*

Table 3. *Results for the Apartment Scenario in Order of Increasing Run 1, Run 2, and TP[min^{-1}], in that Order; Columns Run 1 and Run 2 Indicate Whether the Subject Was Able to Navigate to the Given Target Waypoint in the Respective Run*

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		

potentials (SSVEPs). 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. It also would be interesting to see whether the use of VR technologies like head-mounted displays (HMD), stereo walls or cave automated virtual environments (CAVEs) would affect subject performance and/or motivation. Further research in this particular direction could involve integrating a software SSVEP BCI system that provides feedback within augmented reality environments, which could make this technology applicable for home or office use for both patients and healthy users. Also, this could be particularly interesting for special work environments where the user needs both hands to operate other devices (e.g., astronauts in spacesuits). Another idea would be to facilitate additional brain signals extending this system to a hybrid BCI.

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