Games and Brain-Computer Interfaces: The State of the Art

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Abstract

BCI gaming is a very young field; most games are proof-of-concepts. Work that compares BCIs in a game environments with traditional BCIs indicates no negative effects, or even a positive effect of the rich visual environments on the performance. The low transfer-rate of current games poses a problem for control of a game. This is often solved by changing the goal of the game. Multi-modal input with BCI forms an promising solution, as does assigning more meaningful functionality to BCI control.

1 Introduction

A brain-computer interface (BCI) is a direct connection between the brain and a computer. Most of the time, this connection is unidirectional; using electroencephalography (EEG) or magnetoencephalography (MEG) the activity is measured and classified with a computer. BCIs have been studied mostly in the context of disable patients. Recently more interest is emerging towards BCI for healthy users. BCIs can provide information about the state of the user, and provide a completely new modality for control. Both qualities are very useful for computer games. In this report we will describe the current state of the art of BCI games.

This report is organized as follows. First we will describe existing BCI games. The field is still young, and there are not that many BCI games. Furthermore, most of these games are proofs of concepts. Therefore we included some work on virtual reality and BCI as these experiment with rich visual environments and BCI, and some more artistic interactive explorations using EEG. We will conclude with some general observations and future challenges for research contributing to BCI and games.

2 Previous Work

In this section we describe the current state of the art of BCI and games. We have divided the field into three major groups based on the BCI paradigm used to interact. Most games use characteristic broadband frequencies of the brain, such as the alpha, beta, gamma and mu rhythm as input for the game. Often a function of band-powers is used to quantify relaxation which then drives the game. These games are categorized as using a feedback paradigm. A more

complex type of BCI is based on responses in the brain to stimuli. An example is the P300 response, potential observed around 300ms after a task-relevant stimulus. This can be used to select one out of multiple options presented to the player. A more low-level evoked response is the Visually Evoked Response (VEP), a response to visual information such as flashing patterns that can be modulated by attention (Eason et al. [9]). Games using VEP often implement visual controls on which the user has to focus. The third type of BCI used in games is based on motor control; interaction is then caused by imagination or planning of specific movements. An overview of current BCI-games can be found in Table 1. In the following subsections we will elaborate on the games in the different categories.

2.1 Feedback

Most of the BCI feedback games originate from biofeedback applications. Biofeedback training has been used successfully to treat health problems such as migraine headaches, hypertension, Attention Deficit Hyperactive Disorder (ADHD) etc. Neurofeedback (biofeedback using signals measured from the brain) has been used successfully to alter the brain activity associated with these disorders, however, training is often a boring activity. Neurofeedback implemented in games can overcome this drawback (Pope and Palsson [32]).

While not strictly a game, the neurofeedback in a virtual environment created using VRML by Allanson and Mariani [1] comes close. The amplitudes of the EEG frequency bands are translated directly into control signals, that correspond to changing shape, the appearance or position of a VRML object. An example of a training environment is a simple stacking task, where blocks are to be levitated into position in order to build a tower. Two other games to treat ADHD with neurofeedback were developed by Cho et al. [8]. Both games show a 3D virtual classroom, displaying a challenge that is related to attention on a desk. The feedback is based on the beta-activity in the EEG. A clinical test demonstrates that the games can improve the attention span.

Pope and Palsson decribe a more subtle way to perform neurofeedback. They describe a study in which children with ADHD were treated using neurofeedback. One group used standard neurofeedback, another group played Sony Playstation^{TM} video games where the controller input was modulated by a neurofeedback system developed by NASA; correct brainwave patterns were rewarded with a more responsive controller. Both groups improved substantially and about equally in their inattention and hyperactivity problems. However, the children of the game-version enjoyed their training more, and parents reported to see more improvement.

A game related to neurofeedback is the classic example Brainball [11, 12], a game that can be best described as an anti-game; the goal is to achieve nothing, there are no sounds, blinking lights and no action. Using a headband the EEG of the players is measured. A relaxation score is derived from the ratio between the alpha and beta activity in the EEG signal, which is used to move a steel ball on the table away from the most relaxed player. A display next to the table displays the brain activity and the current state of the game. User evaluations indicate that Brainball players become more relaxed, which places Brainball in the realm of neurofeedback.

Other games have mimicked the concept of relaxation as main interaction

Work	Type	Para.	Sens.	NS	NC	A	b/min
Wang et al. [39]	Game	?	E				
Sobell and Trivich [35]	Vis.	F	E				
Nelson et al. [28]	Game	F	E, M				
Allanson and Mariani [1]	Game	F	E				
Cho et al. [8]	VR	F	E	3	2		
Tschuor [37]	Vis.	F	E	32	2	85%	7.9
Hjelm [11], Hjelm et al. [12]	Game	F	E				
Palke [30]	Game	F	E	1			
Mingyu et al. [27]	Game	F	E	3	1D		
Kaul [13]	Vis.	F	E, M, O	3			
Lin and John [23]	Game	F	E	1			
Shim et al. [34]	Game	F	E	4	2		
Bayliss and Ballard [3]	VR	P300	E		2	85%	
Bayliss [2]	VR	P300	E	5	2		
Bayliss et al. [4]	VR	P300	E	7	2	85%	23.4
Vidal [38]	Game	VEP	E	5	5	80%	180.0
Middendorf et al. [26]	Game	VEP	E	2	3	88%	36.7
Lalor et al. [18, 17]	Game	VEP	E	2	2	80%	5.5
Martinez et al. [24]	Game	VEP	E	6	5	96%	34.9
Pineda et al. [31]	Game	M	E	3	1D		
Leeb et al. [20]	VR	M	E	4	2	98%	6.1
Leeb and Pfurtscheller [19]	VR	M	E		2		
Mason et al. [25]	Game	M	E	12	2	97%	14.0
Leeb et al. [21]	VR	M	E	6	2	92%	4.1
Kayagil et al. [14]	Game	M	E	1	4	77%	6.5
Krepki et al. [16]	Game	M	E	128	2	100%	30.0
Bussink [6]	Game	M	E	32	4	45%	
Lehtonen et al. [22]	Game	M	E	6	2	74%	5.2
Oude Bos and Reuderink [29]	Game	M	E	32	3		

Table 1: Overview of BCI games. Work is sorted by paradigm: F represents feedback settings, in which the user has to adapt by modifying broadband power, M stands for motor tasks, including motor planning, imaginary and real movement, P300 is the P300 response to task relevant stimuli and VEPs are visually evoked potentials. In the sensors column, E indicates EEG sensors, M indicates EMG measurements. The number of (EEG) sensors in indicated in column NS. The performance is expressed in bits per minute calculated according to Wolpaw et al. [40] using the mean accuracy (column A) of classification and number of classes (column NC). Please note that the bit rates can differ with the results reported in the actual references. We have chosen to select the best performing realistic setting, and used the average performance to calculate the bit rate.

modality. A 3D game based on EEG biofeedback is presented by Mingyu et al. [27]. The EEG band power in the major frequency bands is used to determine the speed of a spaceship racing with two other spaceships. Tschuor [37] performs an experiment in which the subjects have to control the computer by relaxation or excitation. In a training session users calibrate the system by relaxing during the sound of the sea by focussing on their breath, and by making math exercises during loud, stressing music which is meant to cause excitation. The EEG is filtered into different frequency bands, for which the power is calculated over trials of 3 seconds for classification. After training the user can control a simplified face that shows the relaxation state of the user.

Palke developed the BCI game Brainathlon [30] that consists of a collection of mini-games controlled by the band power of EEG with neurofeedback in mind. The first game encourages activity in a specified frequency band by moving a red ball towards a finish line. In the second game the goal is to sustain a high activity in a certain frequency band. A high level triggers a timer which counts as long as there is a high activity. In the last game the ratio between to frequency bands is used to balance a ball on a line. The games can be played by two players at the same time. Players were able to consciously increase their alpha activity by playing these games. A game based on Brainathlon was created by Lin and John [23]. A simulated ball moves left or right along a horizontal axis according to a measure of relaxation of the player. Using a single EEG electrode, two players can compete by relaxing more than the opponent like with Brainball.

There are games that use neurofeedback for control instead of therapeutic reasons. One of them is the flight simulator of Nelson et al. [28] that uses commercial CyberLink^{TM} EEG/EMG headband for one-dimensional control in a flight simulator displaying a realistic landscape. Brain-body signals that exceeded a particular power threshold were accompanied by left- or rightward movement in the simulator, accompanied by a roll motion in the same direction. The experiment indicated a significant decline in workload ratings, which is a promising result for BCI and gaming. A similar control is used in the 3D balance game by Shim et al. [34], based on the theta, low beta and mid-beta band power in the left and right-hemisphere. The goal of the game is to learn the player to actively balance the power in both hemispheres. The game is evaluated by measuring the time needed to complete the game. After the first game there is a big decrease in performance, which increases again over time.

A few works of art are based on feedback BCI. A very early brain-computer interface based on feedback is the Brainwave Drawing Game by Sobell and Trivich [35]. An image based on the EEG signal is created and displayed on a monitor in real-time. Forms, shapes, movements and colors are modulated according to band power of the EEG. Due to limited computation power in 1989 the frequency analysis consists of a zero-crossing detector with some basic support for frequency separation. More information is hard to find. A game in which the brain activity indirectly influences the environment is Dream Dreaming game by Kaul [13], which apparently uses band power of the both hemispheres. Low and coherent frequencies cause a boat to submerge into water, releasing different objects. Further relaxation raises a spirit object out of water and move the objects away. Details are hard to find for this game too.

2.2 Event Related Potentials

2.2.1 P300 response

Event related potentials have been studied in virtual environments by Bayliss and Ballard. A head-mounted display (HMD) was used to create a virtual reality in which a P300 response can be evoked by red traffic lights. Users in a go-kart had to break for red traffic-lights in a driving simulation. The ERP can still be obtained and used reliably in this setting. Knowing that the P300 can be used in virtual environments, Bayliss compared the P300 response in virtual and non-virtual environments (Bayliss [2], Bayliss et al. [4]). Subjects were instructed to control 7 objects, such as a light, a stereo etc. in a virtual environment using a P300 BCI. A red sphere highlighted the different objects to evoke a P300 resonse. No significant differences were found for the conditions using a computer monitor and using a head-mounted display, but the results for the HMD were slightly better. Subjects were able to control the objects at reasonable bit rates (see Table 1).

2.2.2 Visually Evoked Potentials

Vidal describes what is possibly the first BCI game [38]. In this game, the user can walk trough a maze using a brain-computer interface based on visually evoked potentials (VEPs). The user can move in four directions by fixating on one of four fixation points off-screen. Brief flashes from a xenon light source projects a red checkerboard between the fixation points. For each fixation point, the diamond-shaped checkerboard lands on a different retinal position, resulting in neural activity on different sites of the primary visual cortex. This VEP is classified and used to move in the maze. The classifier is updated during the game. While being one of the first BCIs, the performance of this system is remarkable (see Table 1). This is partly due to the short trials which results in a higher bit rate, but also the adaptive classification and artifact rejection could contribute to this exceptional performance.

A simpler approach to VEPs is the steady-state visually evoked potential (SSVEP), in which a high-contrast stimulus is modulated at a frequency. The repetitive VEPs have a constant amplitude and frequency. The Air Force Research Laboratory has implemented a flight simulator based on SSVEPs Middendorf et al. [26]. The SSVEP is evoked using white fluorescent tubes modulated at a frequency of 13.25 Hz. In a 30 minutes training session the operators learned to modulate their SSVEP in order to roll a plane in a flight simulator to commanded roll positions using a single SSVEP source. The MindBalance game created by Lalor et al. [17, 18] uses two EEG electrodes on the primary visual cortex to measure SSVEP caused by two different checkerboards inverting at different frequencies (17Hz and 20Hz). The attention on one of the checkerboards is used to balance an avatar on a cord in a complex 3D environment. In general, subjects performed better while playing the game than in the off-line training session. Once every 1.5–5 seconds, an animation of unbalance was displayed for 3 seconds. In this period the player had to use the SSVEP to correct the balance, if this failed the player had a second chance to restore the balance.

One of the advantages of SSVEPs is that stimuli with different frequencies can be used for multi-class control. A 2D racing game with four different directional controls using SSVEP was created by Martinez et al. [24]. Six electrodes

located on the occipital area were used. Blind source separation (BSS) was used to remove artifacts from the data. Two sets of frequencies were used: one with frequencies below 10Hz, and one with frequencies between 10 and 20 Hz; the second set resulted in a slightly better performance of 30 bits/min compared to 26 bits/min for the lower frequencies. A similar interface was developed by Trejo et al. [36] but used for navigation of a map instead of racing.

2.3 Imagined movement

While the evoked responses can be used for interaction with high transfer rates, they depend on the presentation of stimuli. A BCI paradigm that is totally controlled from the brain is based on motor activity. Motor preparation, as for example caused by imagination of movement, can be detected by a period of desynchronization in the alpha and beta frequencies on the motor cortices, followed by synchronization.

Pineda et al. [31] used the mu-rhythm power on motor cortices measured using three electrodes to steer a first person shooter game. The difference in power between the two cortices is used as a binary input; a threshold was determined in a short training session. In effect this corresponds to imagined moment control where rest or simultaneous movement constitutes one class; the other class is formed by activating exclusively the activation of left or right motor cortex. Players learned to control the BCI by experimenting; no instruction was given to the player. Four subjects were trained for 10 hours over the course of five weeks and learned to control the game quickly. Mason et al. [25] implemented a video game in which an imaginary movement would cause the avatar, that was moving at constant speed, to turn left. A trial-based training session was followed by an online game setting in which the subjects could turn at will. They reported their intentions with a switch for validation purposes. A very high accuracy of above 97.2% was obtained for most of the participants, which is partly due to lower frequency of turn commands.

Leeb et al. use a virtual environment in combination with a imagined movement BCI [20]. The virtual environment is a meeting room; subjects could rotate the view to explore the room by imagining left or right hand movement. Relative rotations were used to prevent jumps caused by unstable classification, and a neutral zone prevented fast directional switches. Very high classification rates were obtained (Table 1). A comparison between the performance using a HMD and using a screens show no disturbing effects from the HMD which corresponds to the findings of [4]. A similar environment in which the subjects could move instead of turn was created by Leeb and Pfurtscheller [19]; imagined foot movement is used to move forward in response to a cue. When foot movement was detected without the cue the subject was punished by moving backwards. Imagined right hand movement was used to stop moving. The results indicated that subjects found it difficult to produce the same class for longer periods. Leeb et al. [21] compared the performance using a clinical visualization, and a VE projected using a HMD or using the Cave VR system. The subject had to walk to the end of a street in the VE. All subjects were able to navigate in the different VEs. The usage of VR was stimulating the subjects to perform well. All participants reported that the Cave was more comfortable than the HMD, and both were very much preferred over the BCI training on a monitor.

A slightly different signal is the Lateralized Readiness Potential (LRP). The

LRP is a slow negative EEG shift that develops over the activated motor cortex during a period of about 1 second before the actual movement onset. LRPs for the left and right hand have be used for a Pacman game by Krepki et al. [16]. Pacman makes one step each 1.5–2 seconds, and moves straight until it reaches a wall or receives a turn command. When immersed into the game the user has sometimes the feeling that Pacman moves in the correct direction though the user was consciously not aware of his decision. Krepki et al. use actual movement to evoke a LRP.

Similar to the Pacman game, Kayagil et al. [14] presents a small board game that can be navigated using a series of binary decisions. These decisions are based on a band-power classification discriminating real movement from no movement. The goal of the game is to move towards a goal on the grid while avoiding a trap. Lehtonen et al. [22] also used real finger movements for a simple BCI-game. Three training sessions were used to select subject specific features, to be used with an online adapting classifier. The objective of the game is to move a ball toward the left or right side of the screen as indicated with an arrow by using real finger movements. Three trials were on average required to reach the target.

Bussink [6] outlines the steps towards an imagined movement based BCI game. An classifier based on the CSP algorithm [15, 33] was developed on the BCI-competion datasets, and trained and tested in an online setting fit for games. The work of Oude Bos and Reuderink [29] applies the same type of classifier in a visually rich environment called BrainBasher. This game was evaluated using 15 subjects that played three different game variants: a keyboard controlled graphically rich variant, a BCI variant with the same clinical display as used by Bussink [6], and a graphically rich BCI variant. The keyboard variant was considered easy and boring, while the BCI controlled game resulted in a more challenging and immersing experience. Subjects were more immersed in the graphically rich variant than in the clinical variant, and actually scored higher in the first variant.

3   Discussion

From describing the existing BCI games it becomes clear that the field of BCI and gaming is just starting to define itself. It is a bit disappointing that the oldest BCI game [38] obtained the highest reported transfer rate. However, there are some promising observations to be made. Middendorf et al. [26] report that users intensified the SSVEP by looking away slightly from the stimulus center. For the P300 response, types of stimuli presentation that are possibly more suitable for games are being explored by Bießmann [5]. This seems to indicate that there is still room to improve stimulus presentation in ERP-BCI based games.

Most of the work presented in this report test the feasibility BCIs in visually rich environments. However, comparisons to the clinical settings are not often performed. A few exceptions are Bayliss et al. [4], Leeb et al. [20], Oude Bos and Reuderink [29]; they all indicate that the more game-like experiments are more immersing than the clinical settings, and often resulted in a better performance. Subjects report the games to be more stimulating, and multi-modal feedback is useful [18]. So far BCI seems to be at least as usable in games as in clinical

settings; no negative impact was reported.

According to Fairclough [10], the two main obstacles for applying BCI in real-world settings are assigning intuitive functionality to the BCI, and the limitations on the human information processing in a multi-tasking framework. The latter may possibly be overcome by training [28], the first is a more difficult problem. While BCIs are becoming faster and more accurate, the transfer rate is still to low to use as a control for most games.

This problem can be bypassed by changing the goal of the game, which is done with most of the feedback games. Another solution is to use BCI in combination with another modality. Imagined movement in combination with a keyboard has already been used by Pineda et al. [31], and the modulated Playstation$^{\text{TM}}$ controller described in [32] also uses BCI in combination with another modality. Especially a multi-modal combination of a BCI that uses the players mental state to change the game, a second BCI that can be used to control parts of the game and a traditional controller seems very promising.

With a few exceptions such as Brainball and the modulated Playstation$^{\text{TM}}$ controller, BCI is used in a straight-forward way. In future games, BCI can be used to control extraordinary abilities of the avatars in the game; such as flying, psychokinesis, self healing or extra power [10]. Another way to make the BCI interact more with the game is by monitoring experience. Many people describe a certain video game experiences as "Flow" or a "Zen"-like experience (Pope and Palsson [32], Chen [7]). A brain-computer interfaced game can possibly interact more directly with this experience and improve the experience directly.

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