

# Games, Gameplay, and BCI: The State of the Art

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**Abstract**—Brain-computer interfaces (BCIs) and basic computer games have been interconnected since BCI development began, exploiting gameplay elements as a means of enhancing performance in BCI training protocols and entertaining and challenging participants while training to use a BCI. By providing the BCI user with an entertaining environment, researchers hope to assist users in becoming more proficient at controlling a BCI system. BCIs have been used to enrich the experience of abled-bodied and physically impaired users in various computer applications, in particular, computer games. BCI games have been reviewed previously, yet a critical evaluation of “gameplay” within BCI games has not been undertaken. Gameplay is a key aspect of any computer game and encompasses the challenges presented to the player, the actions made available to the player by the game designer to overcome the challenges and the interaction mechanism in the game. Here, the appropriateness of game genres (a category of games characterized by a particular set of gameplay challenges) and the associated gameplay challenges for different BCI paradigms is evaluated. The gameplay mechanics employed across a range of BCI games are reviewed and evaluated in terms of the BCI control strategy’s suitability, considering the genre and gameplay mechanics employed. A number of recommendations for the field relating to genre-specific BCI-games development and assessing user performance are also provided for BCI game developers.

**Index Terms**—Brain-computer interfaces (BCIs), games, game design, gameplay, review.

## I. INTRODUCTION

**M**ANY people with motor impairments cannot use conventional control devices such as a computer game controller, a mouse, or a keyboard. Individuals with no motor control cannot rely on interfaces such as mouth sticks, eye tracking, or electromyogram (EMG) switches (a switch that can convert electronic signals on the skin into signals that can be used in assistive equipment). Brain-computer interfaces (BCIs) have the potential to enable these users to control and interact with devices and technology using directly measured brain activity. Noninvasive acquisition of neural signals mostly involves electroencephalography (EEG) [1], yet others use functional magnetoresonance imaging (fMRI) [2], functional near-infrared spectrography (fNIRS) [3], and magnetoencephalography (MEG) [4], among others. EEG is most

suitable for BCI gaming because of its high temporal resolution, reaching a few milliseconds, relatively low cost, portability, noninvasiveness, and safety. An EEG-based BCI measures voltage fluctuations resulting from ionic current flows within the neurons of the brain via electrodes placed upon the scalp. It then translates these signals into commands for a program to execute [1]. BCIs afford passive control, direct continuous control, direct point based control, or even hybrid control using multiple BCI strategies. These control types have been used successfully to enable users to communicate [5], create art [6], play games [7], control wheelchairs [8], in rehabilitation [9], to detect awareness in disorders of consciousness (DoC) [10], and to browse the Internet [11]. Recently, there has been increased interest in the application of BCIs for able-bodied users. BCI is being used to monitor the mental state and load of healthy users when completing a task, to provide new control methods and as peripheral input to computer and other devices. This paper provides a review of noninvasive BCI-based computer game interaction and evaluates which BCI control strategies are most suited to various types of gameplay and game genres and how these influence the use of BCI paradigms.

A computer game is an electronic game that involves human interaction with a user interface that generates visual and/or auditory feedback. Typically played against a computer opponent or another human, computer games possess all of the core attributes of traditional games. The players are presented with an overall goal or victory condition and a set of rules, which together define the gameplay. Computer games present the players with the gameplay challenges and act as an arbitrator, using the rules (gameplay mechanics) to define the valid set of actions the player is permitted to take in order to complete the objectives [12]. While generic gameplay challenges such as hand-to-eye coordination, pattern recognition, and logical thinking may be applied across a variety of game genres, many gameplay challenges are genre specific. As such, the design and application of appropriate gameplay challenges represents one of the attributes of excellent game design. Good gameplay is often regarded as more essential than the periphery elements of a computer game (e.g., graphical qualities, story, or narrative) as it represents the fundamental core of any game [13].

In recent years, the application of BCI for interacting with computer games has become increasingly popular among many BCI research studies, with a large upsurge of studies within the last five years (Fig. 1). BCI games are often used to test paradigms or train users how to use BCI and, in recent years, have become increasingly more advanced; including 3-D environments, multiple user objectives, and hybrid control systems incorporating both conventional input devices and multiple BCI techniques. Computer games can be classified by genre based on the abstract gameplay challenges employed within the game. Several BCI surveys have analyzed and reviewed BCI

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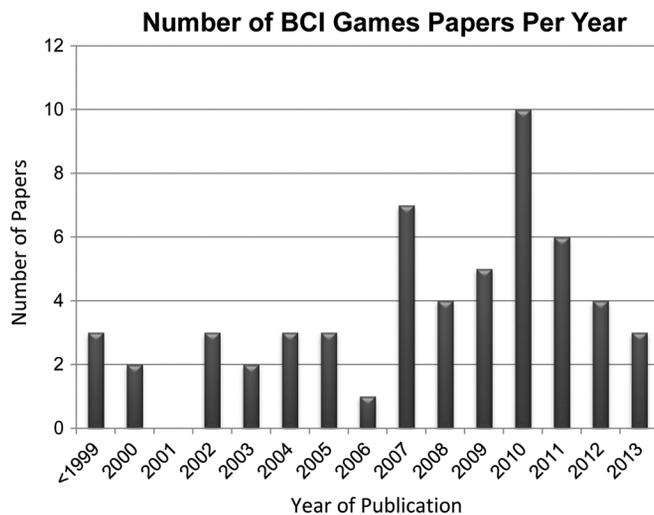


Fig. 1. The number of BCI games papers produced each year. (See Section IV for data details.)

games in terms of human–computer interaction (HCI) [14], multiplayer gaming [15], and virtual reality (VR) applications [16]. Each of these papers focuses on a separate aspect of BCI gaming in detail and provides useful information about specific BCI control strategies for game interaction. However, BCI games have not yet been categorized by genre or reviewed in terms of their application of gameplay challenges. Gameplay is a fundamental aspect to consider when developing a computer game. This work presents an in-depth critical analysis of modern BCI games and begins by presenting a concise review of the fundamental principles of game design, detailing gameplay challenges and associated mechanics applicable to fundamental game genres. This is accompanied by an in-depth review of BCI techniques, highlighting the associated technical and research challenges and current BCI control strategies. Furthermore, the paper evaluates the appropriateness of game genres across leading BCI game implementations and the nature and suitability of the gameplay challenges employed is examined. The paper concludes by making a number of explicit recommendations relating to best practice in terms of the selection of game genres and, more importantly, the use of gameplay mechanics within BCI games. The importance of assessing BCI gameplay performance is also highlighted, along with recommendations for performance assessment. The paper aims to provide a comprehensive point of reference, not only for BCI researchers and BCI-game developers, but also for game developers in general, interested in exploring BCI-game development. It, therefore, does not provide a detailed technical review of BCI signal processing issues. Interested readers are referred to [1] and [18]–[23] for comprehensive surveys of BCI control and signal processing strategies.

## II. BCI CONTROL STRATEGIES AND RESEARCH CHALLENGES

The research and technical challenges associated with the development of BCI games vary considerably depending on the type of BCI paradigm being employed, as well as the genre and inherent gameplay challenges. A brief evaluation of the technical and research challenges associated with using popular BCI

paradigms, and highlighting specific issues relating to their use as control systems in games, is presented below.

### A. Motor Imagery

Motor imagery involves the imagination of the movement of various body parts resulting in sensorimotor cortex activation, which modulates sensorimotor oscillations in the EEG. This can be detected by the BCI to infer a user’s intent. Motor imagery typically requires a number of sessions of training before acceptable control of the BCI is acquired. These training sessions may take a number of hours over several days before users can consistently employ the technique with acceptable levels of precision. Lengthy training sessions are uncommon even within the most complex of games. Instead, designers incorporate tutorials within the gameplay goals of early levels, gradually introducing more complex interaction schemes and gameplay objectives as the game progresses. The use of tutorial levels could be adopted in motor imagery BCI games to cloak or disguise user training so as to enhance the user’s experience.

Unfortunately, the fundamental issue of BCI illiteracy/proficiency where, regardless of the duration of the training session, users are unable to master the control scheme, is common with motor imagery [24]. Motor imagery can also be affected by insufficient attention due to user distraction or frustration [25]. As frustration is common within many computer games (because of flawed game design or a player’s limited skill), BCI games developers must make their games easier than standard computer games. This balancing of gameplay mechanics may involve slowing the game pace or supplying assistive devices inside the game to help the player complete objectives, but at the same time, maintain the entertainment and gameplay challenges that normally hold users’ attention.

### B. Bio/Neurofeedback for Passive BCI Designs

Biofeedback is used to monitor a subject’s mental relaxation. In some cases, biofeedback does not monitor electroencephalography (EEG), but instead bodily parameters such as electromyography (EMG), galvanic skin resistance (GSR), and heart rate variability (HRV). Many biofeedback systems are used to treat certain disorders such as attention deficit hyperactivity disorder (ADHD), sleep problems in children, teeth grinding, and chronic pain. EEG biofeedback systems typically monitor four different bands (theta: 4–7 Hz, alpha: 8–12 Hz, SMR: 12–15 Hz, beta: 15–18 Hz) and challenge the subject to control them. Passive BCI involves using BCI to enrich human–machine interaction with implicit information on the actual user’s state, for example, simulations to detect when users intend to push brakes during an emergency car stopping procedure [26]. Game developers using passive BCIs need to acknowledge that through repetition of game levels the user’s cognitive state will change or adapt. Within the first play of a level, the user will react to things differently than during the second play: for example, the user will be less surprised at an event in the game if he/she is expecting it.

### C. Visual Evoked Potential (VEP)

A VEP is an electrical potential recorded after a subject is presented with a type of visual stimuli. There are several types

of VEPs. Steady-state visually evoked potentials (SSVEPs) use potentials generated by exciting the retina, using visual stimuli modulated at certain frequencies. SSVEP's stimuli are often formed from alternating checkerboard patterns [27] and at times simply use flashing images [28], [29]. The frequency of the phase reversal of the stimulus used can be clearly distinguished in the spectrum of an EEG; this makes detection of SSVEP stimuli relatively easy [30]. SSVEP has proved to be successful within many BCI systems [27]–[30]. This is due to several factors: the signal elicited is measurable in as large a population as the transient VEP and blink movement and electrocardiographic artefacts do not affect the frequencies monitored. In addition, the SSVEP signal is exceptionally robust; the topographic organization of the primary visual cortex is such that a broader area obtains afferents from the central or foveal region of the visual field [31].

SSVEP does have several problems however. As SSVEPs use flashing stimuli to infer a user's intent, the user must gaze at one of the flashing or iterating symbols in order to interact with the system. It is, therefore, likely that the symbols could become irritating and uncomfortable to use during longer play sessions, which can often last more than an hour [32]. Gamers tend to spend long periods playing computer games. Also, games that use flashing stimuli such as SSVEP would be inappropriate for users with photosensitive epilepsy [27]. SSVEP game developers, therefore, need to consider that SSVEP can only be used for short periods of time without causing irritation to the user. Alternatively, developers could include sizable breaks between SSVEP input sessions or create games that would only be played for short periods of time. SSVEP also requires each symbol to complete an animation cycle allowing for the correct symbol to be chosen; a characteristic that can slow gameplay at points where a player needs to complete a decision related challenge. Game developers, therefore, need to design games that keep the user entertained throughout and around these instances.

Another type of VEP used with applications is the P300 potential. The P300 event-related potential is a positive peak in the EEG that occurs at roughly 300 ms after the appearance of a target stimulus (a stimulus for which the user is waiting or seeking) or oddball stimuli [33]. The P300 amplitude decreases as the target stimuli and the ignored stimuli grow more similar. The P300 is thought to be related to a higher level attention process or an orienting response. P300s, in general, are detected at Fz, Cz, and Pz, as defined by the International 10–20 system electrode positioning nomenclature [1]. To elicit a P300 response, probe stimuli are present in the visual, auditory, and tactile modality. Using P300 as a control scheme has the advantage of the participant only having to attend limited training sessions. The first application to use the P300 model was the P300 matrix [34]. Within this system, a subject would choose a letter from a grid of 6 by 6 letters and numbers. The rows and columns of the grid flashed sequentially and every time the selected "choice letter" was illuminated the user's P300 was (potentially) elicited. However, the communication process, at approximately 17 characters per minute [35], was quite slow. The P300 is a BCI that offers a discrete selection rather than a continuous control mechanism. In [34] the argument was raised that a goal-selection approach resembles the natural functioning of

the brain and does not require the brain to learn something completely new. This is the advantage of P300 use within games: the player does not have to teach himself/herself how to use a completely new control system and so only has to undertake short training instances, to learn the gameplay mechanics and basic use of the BCI paradigm.

As the P300 evoked potential requires "oddball" objects the selected stimuli have to be vastly different than other stimuli within the game, possibly compromising the game's aesthetic qualities. Game developers using P300 will need to integrate the oddball stimuli into the game environment in a creative and inconspicuous way; this could include only changing the object's shape at those times when the game requires a decision using the P300 evoked potential. To evoke the P300 evoked potential, the flashing stimuli to be used can cause the same problems as SSVEPs within games (visual fatigue and risk of photosensitive irritation).

### III. GAME GENRES

The primary goal of a game is to entertain the player, and his/her enjoyment is directly influenced by the designer's application of fundamental game design principles. However, games often contain design flaws (inconsistent or unnecessarily complex gameplay, unappealing aesthetics, or awkward controls) causing player dissatisfaction [12]. Satisfaction is stated as an important element of HCI when analyzing BCI games [14]. Gameplay is often regarded as the most important factor when trying to entertain and satisfy a player. Gameplay must allow the player to control the game without hindrance, define clear and achievable objectives that represent an appropriate challenge, and reward the player with a sense of achievement upon completion. It is, therefore, important to review popular game genres, define the associated gameplay challenges, and evaluate the suitability of these gameplay challenges for use in BCI gaming. Adams [12] states that the main game genres fall into seven specific types; two of these genres have yet to be utilized in BCI games (sports and adventure games). In the following sections, games are organized into genres using their most prominent features. This is because some of the games could be considered hybrid genre games (games which cross genres, combining features not typically found together).

#### A. Action Games

Action games typically involve gameplay challenges that test the player's physical skills, such as the player's reaction times, hand-to-eye coordination, and spatial awareness inside the game environment. Action gaming is the most popular and diverse of all computer game genres encompassing arcade, platform, and first person shooter (FPS) games. Typically, action games employ time-critical gameplay challenges with clear objectives that require quick decision making in response to changes inside the game environment. As BCI games often require rather lengthy periods to generate the correct signal to trigger a control (within noncontinuous control methods), many compromises and workarounds are used within this genre of BCI game. BCI action games typically allow lengthy periods of time for the player to make a decision or assist the player to reach an objective (within continuous control methods).

### B. Strategy Games

Strategy games challenge the player to complete objectives through specifically planning a series of actions taken against one or more opponents. Strategy games originate from board games such as *Chess* and *Risk* and can be divided into two broad categories depending upon their gameplay type: real-time and turn-based strategy games. Real-time strategy (RTS) games are played in “real time,” requiring players to utilize their time management skills and reaction speed in order to make important strategic decisions. The complexity of RTS games make these a problem for BCI, as they typically require the players to control several gameplay objects in parallel. BCI is more suited turn-based strategy gameplay as BCIs often tend to require longer input sampling periods to provide simple controls accurately. Turn-based BCI strategy games would allow a user to accurately choose an action (taking as long as the player/system requires), then to complete an action and wait for the computer or human player to plan and execute their next move (*Chess* is a good example of a strategy game).

### C. Role-Playing Games

Role-playing games (RPGs) primarily focus on exploration gameplay challenges, incorporating secondary logistical, conflict, or tactical challenges. RPGs often allow the player a great deal of freedom in navigating through the game world and, therefore, each player’s experience of the game can vary significantly. The development of a suitable BCI control system that addresses RPG gameplay challenges would, therefore, represent a significant challenge (most RPGs feature several different gameplay elements). However, BCIs could be used for certain elements of the game, such as decision making, simple movement around the landscape, or passive BCI changing the gameplay type. A turn-based RPG (much like a turn-based strategy game) is more suited to BCI because gameplay within turn-based RPGs is generally not time critical.

### D. Adventure Games

Adventure games provide exploration and puzzle-solving challenges. Adventure games typically revolve around an engaging central story that acts as a vehicle to structure the gameplay and experiences. Adventure games typically incorporate decision-based gameplay developed around a central story, often presenting many different routes for a player to follow throughout the game. Developing an adventure game is, therefore, a more challenging undertaking than developing a pure action game. Lengthy development time, multiple story paths, and the decline in popularity of this genre have led to less emphasis on adventure games in the development of BCI games. A simplistic adventure game, however, could be used for BCI, with the player being given a set number of options at each interval.

### E. Sports Games

Sports games are similar to action games in that they test the player’s reaction times, hand-to-eye coordination, and spatial awareness. Sports games typically simulate a real-life sport and are based upon the same rules and objectives that govern that sport. Depending upon the type of sport being simulated, sports

games can employ continuous control or trigger-based control. For example, in soccer games, continuous control is required to control a player upon the field within normal play, yet when in the penalty stages of the game the player must decide what area of the goal they wish to aim for and the power they wish to kick the ball with (the player has considerable time to make these decisions in most soccer games). BCI could be employed within sports games to control specific elements of the gameplay such as movement during set plays, taking a penalty kick and/or controlling the goal keeper where movement direction can be limited.

### F. Simulations

Simulation games attempt to accurately recreate the feeling of participating in an action that is real or imaginary. Simulations often involve players participating in activities that would be either dangerous (driving an F1 racing car) or unfeasible (assuming the role of mayor of New York) in real life. Flight simulators (one of the most popular types of simulators) require a player to take control of an aircraft and fly it from point to point, going through complex procedures for landing, takeoff, and continuous flight. Other simulations such as management simulations challenge the player to make decisions inside an accurately simulated management environment; the gameplay in these games is typically based upon several choices the player must make. Management simulations would be ideal for use with a selection-based BCI. BCIs often use virtual training environments to test paradigms and train subjects for use within real environments [36], [37]. As many BCI training protocols employ a game or virtual environment to train and use, these stages could be considered BCI simulation games.

### G. Puzzle Games

In the puzzle game genre, puzzle solving requires logical thinking, deductive reasoning, pattern recognition, and intrinsic or extrinsic knowledge. The player’s objective in puzzle games is to complete the puzzle within the game’s set rules (time, amount of moves allowed, or the type of moves allowed). Puzzle games challenge players to think logically, often using pattern recognition and coordination-related challenges (forcing the players to make quick decisions under pressure, for example, *Tetris* or *Hexic*) and challenge the player’s understanding of processes and game mechanics. Slow turn-based puzzle games would be suited toward BCI rather than the faster speed puzzles (that focus on challenging players’ coordination and reactions as well as their logical thinking). A turn-based BCI puzzle game would allow players to use the BCI to make simple choices within a set time period; this would allow the game to collect the required amount of data to accurately interpret the player’s intention and carry out the command associated with the action.

## IV. GENRE-SPECIFIC BCI GAMES: THE STATE OF THE ART

Within this section, we present the current state-of-the-art BCI games, evaluate BCI games, game genres, and BCI techniques, and the application of gameplay challenges within exemplar BCI games. Given the nascency of the field of BCI-game interaction, it was decided to include conference papers, instead

TABLE I  
 JOURNALS. THIS TABLE INCLUDES PAPERS DETAILING THE BCI PARADIGM, THE TYPE OF SENSOR, THE NUMBER OF SENSORS, THE NUMBER OF CHANNELS, THE NUMBER OF SESSIONS, THE NUMBER OF SUBJECTS, THE MEAN ACCURACY OF THE TRIALS, THE YEAR PUBLISHED, AND THE GAME GENRE. THE PAPERS ARE LISTED IN CHRONOLOGICAL ORDER

Paper/Game/Device	Type	Paradigm	Sensors	Number of Sensors	Number of Channels	Sessions	Subjects	A %	Year	Genre
A virtual Reality Testbed for Brain-Computer Interface Research [95]	Game	P300	EEG	8		1	5	83	2000	Simulation
Learning to Control Brain Rhythms: Making a Brain-Computer Interface Possible [83]	Game	Motor	EEG	4	3	10	5		2003	Action
Critical Decision-Speed and Information Transfer in the "Graz Brain-Computer Interface" [85]	Game	Motor	EEG	2	2	3	4	83	2003	Action
Steady-State VEP-Based Brain-Computer Interface Control in an Immersive 3D Gaming Environment.[27]	Game	SSVEP	EEG	2	2	1	6	89	2005	Action
Walking from thoughts: Not the muscles are crucial but the brain waves. [97]	Game	Motor	EEG	3	3	2	3		2005	Action
Self-regulation of Slow Cortical Potentials: A New Treatment for Children With Attention-Deficit /Hyperactivity Disorder [82]	Game	biofeedback	EEG	2	2	30	23		2006	Action
Brain-Computer Communication: Motivation, Aim, and Impact of Exploring a Virtual Apartment [52]	VR	Motor	EEG/EMG	22+3	3	2	10	67.6	2007	Simulation
The Berlin Brain-Computer Interface (BBCI) – towards a new communication channel for online control in gaming applications [45]	Game	Motor	EEG	128	2				2007	Action
Fully online multicommand brain-computer interface with visualneurofeedback using SSVEP [96]	Game	SSVEP	EEG	6	6	1	5	96	2007	Action
A high performance sensorimotor beta rhythm-based brain-computer interface associated with human natural motor behaviour [58]	Game	Motor	EEG	29	1	2	9	80	2007	Action
Online Classification of Single EEG Trials During Finger Movements [100]	Game	Motor	EEG	6		4	10	80	2008	Action
Playing Pinball with non-invasive BCI [84]	Physical Game	Motor	EEG			10	7		2009	Action
The MindGame: A P300-based brain-computer interface game [47]	Game	P300	EEG	10		1	11	65	2009	Strategy
Affective Pacman: A Frustrating Game for Brain-Computer Interface Experiments [103]	Game	Biofeedback	EEG						2009	Action
EEG Control of a Virtual Helicopter in 3-Dimensional Space Using Intelligent Control Strategies [39]	Game	Motor	EEG	64	4	11	4	67	2010	Action
Light on! Real world evaluation of a P300-based brain-computer[104]	Game	P300	EEG	8		8	9	80	2012	Simulation
Hangman BCI: An unsupervised adaptive self-paced Brain-Computer Interface for playing games [57]	Game	Motor	EEG	64	9	5	5	70	2012	Puzzle
Switching between Manual Control and Brain-Computer Interface Using Long Term and Short Term Quality Measures [77]	Game	Motor	EEG	6	3	1	10	66	2012	Action
Steady State Visual Evoked Potential-based Computer Gaming on a Consumer-grade EEG Device [111]	Game	SSVEP	EEG	8		2	20	80.4	2013	Puzzle
Thinking Penguin: Multi-modal Brain-Computer Interface Control of a VR Game [112]	Game	Hybrid	EEG	5	2	2	14		2013	Action
Two Brains, One Game:Design and Evaluation of a Multi-User BCI Video Game Based on Motor Imagery [113]	Game	Motor	EEG	16	8	4	20	73.9	2013	Action
alphaWoW   BrainGaming [48]	Game	Biofeedback	EEG	4	4	1	42	74	2010	RPG

TABLE II

MAGAZINES AND CONFERENCE PAPERS. THIS TABLE INCLUDES PAPERS DETAILING THE BCI PARADIGM, THE TYPE OF SENSOR, THE NUMBER OF SENSORS, THE NUMBER OF CHANNELS, THE NUMBER OF SESSIONS, THE NUMBER OF SUBJECTS, THE MEAN ACCURACY OF THE TRIALS, THE YEAR PUBLISHED, AND THE GAME GENRE. THE PAPERS ARE LISTED IN CHRONOLOGICAL ORDER

Paper/Game/Device	Type	Paradigm	Sensors	Number of Sensors	Number of Channels	Sessions	Subjects	A %	Year	Genre
Neurological gaming environments [93]	Game	Biofeedback	EEG							Action
Brainwave Drawing Game [89]	Game	Biofeedback	EEG						1989	Simulation
Navigating Through Virtual Flight Environments Using Brain-Body-Actuated Control [88]	Game	P300	EEG/EMG			10	12	79	1997	Simulation
Mind over virtual matter: using virtual environments for neurofeedback training [90]	Game	Biofeedback	EEG						1999	Puzzle
Brainball – using brain activity for cool competition [79]	Physical Game	Biofeedback	EEG	3	3	1			2000	Action
Attention Enhancement System using virtual reality and EEG biofeedback [91]	Game	Biofeedback	EEG			8	50		2002	Simulation
Walking through a virtual city by thought [87]	Game	Motor		3	3		3		2004	Simulation
Development of EEG Biofeedback System Based on Virtual Reality Environment [80]	Game	Biofeedback	EEG	3					2005	Simulation
Game-like Training to Learn Single Switch Operated [43]	Game	Motor	EEG	5	1	6	10	94.5	2007	Action
Neuroprosthetic Control Implementation of a 3-Dimensional Game for developing balanced Brainwave [94]	Game	Biofeedback	EEG		4	5	10		2007	Simulation
Binary EEG Control for Two-Dimensional Cursor Movement: An Online Approach [98]	Game	Motor	EEG	1	1			77	2007	Action
BrainBasher: a multi-modal BCI game for research and demonstration [81]	Game	Motor	EEG	32	3	2	15	69.4	2008	Simulation
Bacteria Hunt: A multimodal, multiparadigm BCI game [28]	Game	Biofeedback /Motor/ P300	EEG						2009	Action
Playing Tetris with Non-Invasive BCI [54]	Game	P300/Motor	EEG						2009	Puzzle
P300 BCI with Stimuli Presented on Moving Objects [55]	Game	P300	EEG	7	6	4	12	65	2010	Puzzle
Avatar navigation in virtual and augmented reality environments using an SSVEP BCI [86]	Game	SSVEP	EEG	2	2		7	91.7	2010	Simulation
Evaluating user experience with respect to user expectations in brain-computer interface games [109]	Game	SSVEP/P300	EEG						2010	Action
NeuroWander: a BCI game in the form of interactive fairy tale [101]	Game	Biofeedback	EEG						2010	Action
MindTactics : A Brain Computer Interface Gaming Platform [102]	Game	Biofeedback	fNIR						2010	Action
Evaluating a Brain-Computer Interface to Categorise Human Emotional Response [110]	Game	Biofeedback	EEG				20		2010	Puzzle
An Virtual Vehicle Control Game for Online Brain Computer Interface Feedback Training [116]	Game	Motor	EEG	32	2	1	1		2010	Simulation
EEG-based Continuous Control of a Game using a 3 Channel Motor Imagery BCI [7]	Game	Motor	EEG	24	3	4	3	80.2	2011	Action
Brain Chess – Playing Chess using Brain Computer Interface [46]	Theory	P300	EEG						2011	Strategy
Brain Computer Interface based 3D Game for Attention Training and Rehabilitation [108]	Game	Biofeedback	EEG		2		10		2011	Simulation
Using EEG pattern analysis for implementation of game Interface[117]	Game	Motor	EEG	1	1	5	82		2011	Action
Augmented control of an avatar using an SSVEP based BCI [49]	Game	SSVEP	EEG						2012	RPG
Designing a Brain-Computer Interface controlled video-game using consumer grade EEG hardware [115]	Game	SSVEP	EEG	14	8	1	8	85	2012	Strategy

TABLE III

OTHER, INCLUDING MASTERS THESIS' AND ONLINE ARTICLES. THIS TABLE INCLUDES PAPERS DETAILING THE BCI PARADIGM, THE TYPE OF SENSOR, THE NUMBER OF SENSORS, THE NUMBER OF CHANNELS, THE NUMBER OF SESSIONS, THE NUMBER OF SUBJECTS, THE MEAN ACCURACY OF THE TRIALS, THE YEAR PUBLISHED, AND THE GAME GENRE. THE PAPERS ARE LISTED IN CHRONOLOGICAL ORDER

Paper/Game/Device	Type	Paradigm	Sensors	Number of Sensors	Number of Channels	Sessions	Subjects	A %	Year	Genre
Computer Game Control through Relaxation-Induced EEG Changes [92]	Game	Biofeedback	EEG	32		12	4	85	2002	Simulation
Navigation in virtual environments through motor imagery [59]	Game	Motor	EEG	2	2		4	98	2004	Simulation
Towards the first HMI BCI game [99]	Game	Motor	EEG	32	4	1	1	45	2008	Action
Using 3D video game scenarios and artificial neural networks to classify brain states for a brain computer interface [106]	Game	Motor	EEG	64			10	60	2010	Action
Social interaction in a cooperative brain-computer interface game[114]	Game	P300/SSVEP	EEG	5	5	1	20		2011	Puzzle

of focusing exclusively on research published in journal papers, which is often typical in review papers. There are a relatively small number of peer-reviewed-journal-based BCI-game papers, whereas many of the examples of BCI games in specific genres have only been reported in conference proceedings. It is, however, important to note that many conference paper reports often only demonstrate proof-of-concept studies in which the BCI performance is less rigorously assessed, and are often not subjected to the same scrutiny as peer-reviewed manuscripts. Google Scholar [38] was chosen as the database used to assess the extent of activity in the field as it contains information on all types of manuscripts (as opposed to other databases which only include journal manuscripts). The search terms “BCI computer games” and “BCI games” were used. The games selected were chosen because they were most similar to conventional games.

Data from each study involving a BCI game are presented in Tables I–III. The games are categorized based on genre, with each system being evaluated in terms of the application of genre-specific gameplay requirements, and how each work addresses the associated technical and research BCI challenges. The accuracy of each system is also evaluated and contrasted with similar approaches within the games genre and BCI control method type. As can be seen from Table I, there is a stark contrast across the different studies in terms of the reported BCI setup, including number of electrodes/EEG recording channels and training sessions involved. In some cases, many aspects have not been reported. This suggests a need for a more consistent reporting strategy to help compare methods and define the best BCI interaction methods for each genre. Overall, it is clear that there is a growing interest in the field, with over 50 studies reported and a doubling of the number of papers published since 2007 compared to prior to that date, as shown in Fig. 1.

Fig. 2 shows the percentage of BCI games within each game genre. Fig. 3 shows the percentage of BCI games for each BCI type or interaction method. As can be seen, there are clearly dominant BCI-game genres and types, with the action genre being the most popular. Motor imagery is the most popular

## BCI Game Genres

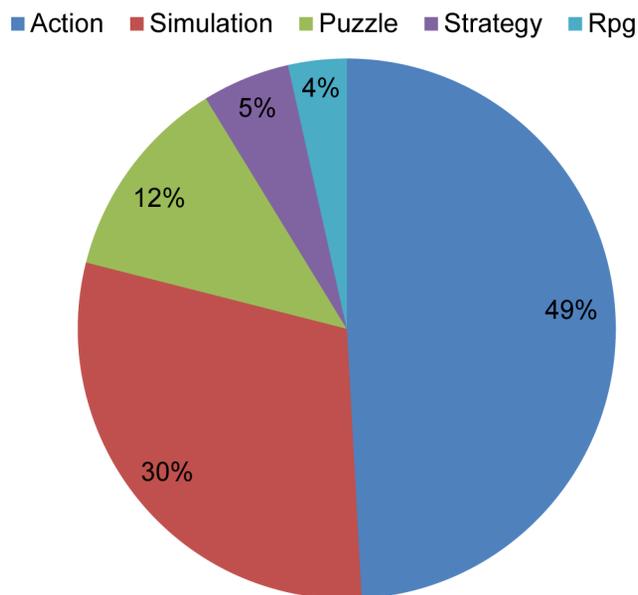


Fig. 2. The percentage of BCI games within each game genre. The action genre dominates BCI gaming with 49% of games being action games.

brain–computer game control mechanism. This section highlights examples of the various types of games in these genres; their associated advantages and disadvantages from a gameplay perspective, as well as various strategies that can be adopted to enhance the games interaction while maintaining the characteristics of good gameplay.

### A. Action

The action genre is the most popular genre employed in BCI computer games (Fig. 2). As action games typically include fast moving gameplay, it is surprising that this genre is so popular within the field of BCI gaming. Motor imagery seems to be the most popular BCI control method to use within the action genre;

## BCI Games Paradigms

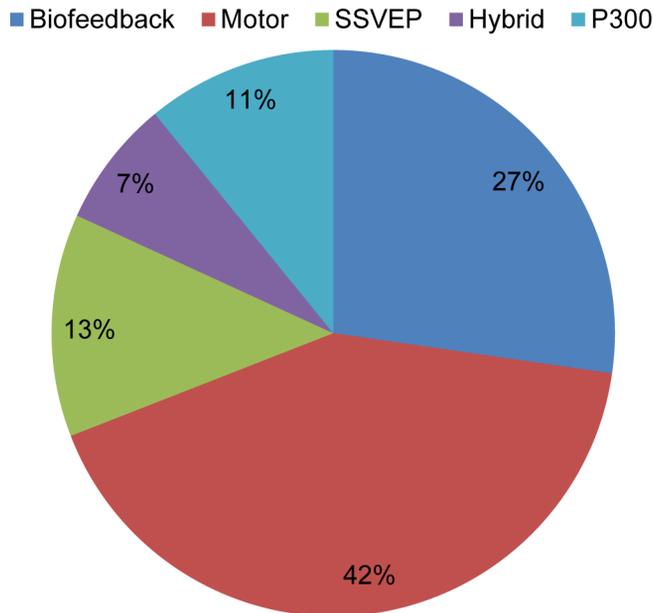


Fig. 3. The percentage of BCI games for each BCI interaction method.

this is because motor imagery often provides a continuous control method within BCI games. A continuous control paradigm enables a player to have control of an element of the game (for example, player movement) continuously over an extended period, not simply discrete response control.

Motor imagery games typically involve the player controlling a virtual object's movement, such as in [7] where the player is challenged to control a spacecraft and avoid incoming asteroids inside a 2-D environment (Fig. 4). Asteroids move downward requiring the player to move his spacecraft horizontally across the screen to safety (Fig. 4). The asteroids drop quite slowly and do not increase in speed throughout the game. However, within later levels, the asteroids increase in number and begin to move in diagonals. This follows the typical difficulty progression found within most action games. Graphically, the game is quite appealing but also distracting, with a moving background and moving noninteractive objects (shooting stars). This was found not to be detrimental to the control method, with most users performing well in trials. Yet, using visual distractions inside an action game is not recommended [11] as users need to see targets and objects within the game clearly, to accurately test their reactions and control of the system (users may attempt to dodge objects unnecessarily). The space game is also timed according to the traditional timing of a normal motor-imagery-based training protocol, making it easier to transition from a training paradigm to the game; users normally progress from a standard ball-basket training game to the space game, where the timing is consistent across training and games. The game has also been shown to enhance performance in both able-bodied and spinal cord injury users compared to a standard ball control paradigm [7], [17].

BCI action games also incorporate object collection objectives [39], [40]. Object collection objectives work well with



Fig. 4. An example of the space game graphics that may be slightly distracting to the user. In this screenshot, the player must avoid the asteroid (gray object to the right) yet is allowed to pass freely through the background image of the moon (large round object on the left) [7].



Fig. 5. Three-dimensional helicopter game: The experimental paradigm and virtual world. The colors correspond to the different phases of a trial: black for reset, green for search, blue for final approach, and red for success [39].

motor imagery, as players are challenged to navigate through virtual environments using BCI control. One example [39] was used as an experimental tool to provide full 3-D control to a player in virtual space using an EEG-based BCI. As noninvasive BCI-based 3-D control had never been achieved within a game, this represents a clear advancement in the field of BCI games, although 3-D control had been achieved using noninvasive BCI, as described by McFarland *et al.* [41]. In [39], the player controlled a virtual helicopter adjusting both vertical and horizontal movement of the vehicle with constant speed. The player's objective within the game is to fly through a series of rings within a simulated-city-like environment. Motor imagery using both the players' hands was used; subjects imagined moving their right hand to go right, their left hand to go left, both hands to move up, and at rest to move down. A screenshot of the game and the path required to enter a ring is shown in Fig. 5.

As the BCI allowed the player full freedom of movement, the player could explore the environment as he/she wished, yet the objective of the game was to fly through floating rings within the environment. The player would be required to align himself/herself with the floating rings and then proceed to fly through them. As the player had no control over the helicopters speed, this was quite difficult. To remedy this, a "cone of guidance" was used to assist the players on their final approach to the target rings. The "cone of guidance" was a large cone-shaped object

surrounding the rings but was invisible to the player. This invisible cone only allowed the player to enter the ring from an approach no more than  $60^\circ$  from the target hole; this made the hole significantly easier to transverse and lessened the difficulty of the game (Fig. 5). The “cone of guidance” is an example of how to assist players when using difficult to master BCI controls, especially within action games that expect quick, accurate actions.

SSVEPs have also been used within the action genre. In *MindBalance* [27], a player must balance an onscreen avatar (a graphical representation of the user) across a tightrope using SSVEP symbols. For *MindBalance*, the decision was made to choose black and white checkerboard pattern symbols as they produced a more pronounced SSVEP (this is also noted by other BCI game studies [42]). In *MindBalance*, two checkerboard patterns are placed on either side of the onscreen avatar. Each checkerboard is phase reversed at two selected distinct frequencies. The game begins with a brief training period, within which the subject is told to gaze at the left or right checkerboards. Within the actual game, the character walks toward the player (toward the screen/camera) and stumbles either left or right every 1.5–5 s. The player must correct the character during these stumbles by focusing upon the checkerboard on the opposite side of the avatar; this corrects the character’s balance. As the avatar begins falling, the player will correct the avatar based upon the most recent 1 or 2 s of EEG obtained. The game is such that the avatar will never walk for more than 5 s without losing balance, and it is possible for the player to focus on one of the two checkerboard patterns to determine the side to which the loss of balance will occur (forcing the avatar to lose balance in that direction, allowing the player to predict what stimulus he/she must concentrate upon; this is a game strategy). *MindBalance* is an example of a simple decision making action game that uses an exciting situation (balancing on a tightrope) and quick decisions to excite the player. Because *MindBalance* is set within a dynamic 3-D environment with visually appealing graphics, the player becomes more immersed in the game. Most importantly, the symbols are clear and large within the dynamic environment, allowing the player to concentrate upon them without being distracted.

Within the action genre the highest accuracies were encountered when using SSVEPs (90% [27]). This suggests that SSVEPs may be more suited toward the action genre than other BCI paradigms. Yet some studies dealing with motor imagery within the action genre achieved an accuracy of 94.5% [43]. The high level of accuracy may have been caused by the simplicity of the gameplay employed within the particular study (jumping over hills at a slow speed using a singular control, also allowing the subject to jump when a hill is not in the avatar’s path). Several other simple motor-imagery-controlled action games also achieved high levels of accuracy [7], [44], [45]. In many of these games, the gameplay was significantly slower or more simplistic than the gameplay found within traditionally controlled action games. This suggests that, with significant gameplay changes, BCI action games can provide sufficient accuracy to provide a rewarding gameplay experience for the player.

## B. Strategy

Few examples of the strategy genre exist within BCI games, largely due to the complexities inherent in their development. An example of a BCI strategy game is *Brain Chess* [46], which uses the P300 visually invoked potential to detect objects chosen by the player. A card game was used to train both the users and the system using election of the oddball P300 signal (when the user found the odd card, the signal was elected). This is an excellent example of how to integrate training into the game, yet the use of *Chess* pieces rather than cards within this tutorial may have been more appropriate, being more consistent with the game.

The game system uses a similar approach to the P300 speller [34] by allowing a player to choose his/her *Chess* piece, via the P300 flashing lines method. Once a piece has been selected, each valid move is shown to the player and he/she must focus on the desired selection to move the *Chess* piece. As *Chess* is a turn-based strategy game, the player could take as long as necessary to make a decision, and then communicate the decision via P300. This approach is very appropriate for the turn-based style of strategy game and deals with noncomplex movements within a game that incorporates complex strategies. Graphically, the game is quite basic, yet it is appropriate for the genre and stays true to the characteristics of the game of *Chess*.

Another strategy game that also uses P300 is the *Mindgame* [47], which involves a player visiting trees within a 3-D game board. The player’s task is to strategically control the avatar’s path from tree to tree. The player must choose the quickest or shortest route between the trees as the player’s “confidence,” or the measure of the quality of the P300, affects the number of steps the avatar takes between trees. This is a great example of how gameplay can directly encourage a player to produce better quality signals, and this allows the player to learn quickly how to produce the correct controls for the game.

## C. Role-Playing Games

As role-playing games involve many different aspects of gaming (combat, strategy, exploration, experience, and item gathering), producing a simple BCI control element to control all gameplay aspects would be very difficult and likely compromise the player’s gameplay experience. In *Alphawow*, one gameplay aspect was controlled via BCI [48]. *Alphawow* runs on a modified version of the popular massively multiplayer game *World of Warcraft* [48]. Within the game, the player has full control of a character via keyboard and mouse (movement control, attack controls, and other aspects of normal control within the game). Yet, one aspect of the character’s actions is controlled via passive BCI: the character’s form. The character within *Alphawow* has two forms: an elf and a bear. The elf form allows them to attack enemies from a safe range and the bear allows them to attack from close range (the bear is also more resistant to attacks). The “shape shifting” in the game is controlled via the user’s parietal alpha activity. This means that when the player is relaxed, he/she will remain in elf form (the player is safe and attacking from a distance), and when the player becomes agitated, he/she will transform to bear form (the player is under attack and needs to defend himself/herself



Fig. 6. The player's Avatar is placed on a tightrope between two SSVEP checkerboards. The player must correct the avatar's fall by focusing on the right symbol [27].

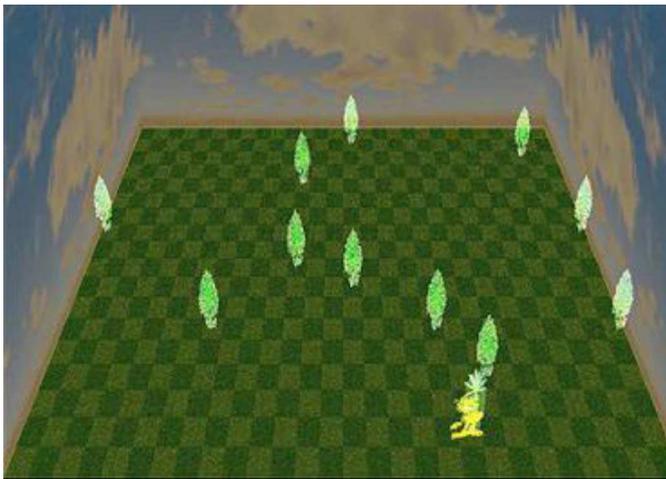


Fig. 7. A screenshot from *The Mindgame*, a player moving the avatar to a tree selected by SSVEP-controlled BCI [47].

or attack the enemy). In *Alphawow*, the player can begin to play immediately (without training). As there are many differences in brain activity between users, and brain activity also changes over time, a normalization function was applied. This means that even if the player has a stressful disposition, they will still be able to change into an elf, if they relax relative to their general state of mind. Utilizing the normalization function helps to avoid difficulties relating to repetition when monitoring the player's mental state, such as the player replaying a difficult stage of the game. The normalization function also negates the inclusion of a training stage within the game. This is a good example of how passive BCI can enhance a player's experience with an existing game. A screenshot of the *Alphawow* character changes is shown in Fig. 8.

SSVEP has also been used to control other single aspects of *World of Warcraft* [49], such as avatar moment and some action commands. However, action commands needed to be chosen via a traditional controller and then selected via the BCI interface. As SSVEP depends upon flickering stimuli, this control method may become visually fatiguing when used for a long session, as outlined earlier. As *World of Warcraft* is associated with long



Fig. 8. *Alphawow* example: Stress changes the user's character into a bear. To change back into their natural elf form they try to enter a relaxed state. The orange bar in the top left of this screenshot provides feedback to the player on his/her current alpha state [48].

play sessions [50], SSVEP may not be the ideal control method for the game.

BCI games within the RPG genre are extremely rare. This is mainly because of the number of different gameplay elements included in a modern RPG. *World of Warcraft* was chosen in each case possibly because it is particularly popular. Within each example only one gameplay aspect of the game was controlled via BCI. This suggests that the genre could be used with hybrid BCI (the use of BCI and traditional controls), yet not depending on full BCI control for every gameplay aspect.

#### D. Simulations

Simulation games associated with BCI are mainly used for training users inside a virtual environment (VE) on how to use a BCI interface. Simulations are often conducted before dangerous tests, such as in [37], where a user was instructed to apply emergency breaks using BCI control within a vehicle simulation. This simulation intended to show that a user's intention to use the car's breaks was detectable before they could physically push the brake pedal. As the simulation was only intended to test this possibility, the simulation's objective and gameplay challenge is very minimal (brake the car within a certain distance) and it, therefore, cannot be critically evaluated as a simulation game.

Some simulations allow the player control of an avatar inside a VE. One example of this is the motor-imagery-controlled navigation of a virtual apartment [51]. In this simulation, a player navigates throughout an apartment along predefined pathways; at each doorway or junction, the player chooses the next predefined pathway to take using motor imagery. At each junction, the player is given a small visual cue on screen showing the possible routes. The subject then concentrates upon one imagined movement for 2 s. The player is then given feedback, showing how strong his/her signal was (the arrow growing or shrinking corresponding to the signal strength or confidence in the translated signal); this feedback allows the player to improve his/her ability to modulate sensorimotor rhythms to provide a superior signal. After the player has given the correct response, the on-screen avatar animates a rotation; this technique prevents jumps in the rotation caused by unstable classification (if the player

has full motor-imagery-based control of the avatars rotation). Yet, again, the objectives within this game are limited, with the player only having to complete directional decisions to navigate around the virtual apartment.

Simulation games have allowed participants to train on how to control other devices using a BCI. For example, in [52], a tetraplegic participant controlled a wheelchair in a virtual street using both feet motor imagery. The participant's objective was to navigate to the end of a street, avoiding obstacles and stopping to undertake discussions with virtual characters along the route. In order to activate a conversation, the user had to exhibit extremely precise control over his/her wheelchair, stopping in very close proximity to the virtual character. This is an example of a simulation game teaching a player how to control a real-world device (a motor-imagery-controlled wheelchair). This type of game could also be used to conduct virtual tours as a learning or teaching game, with each conversation with an avatar being educational.

Simulation games can use a range of BCI control methods. In [44], motor imagery was used to enable participants to look around a conference room and provide accurate results, with three subjects reaching 77% –100% classification accuracy. Once again, the high levels of accuracy within this study may have been influenced by the simplicity of gameplay within the study (subjects only needed to turn left or right). Simulations had the highest average accuracy of all games reviewed. This may be due, in part, to their slow gameplay, allowing subjects to adjust and learn how to control the BCIs. Simulation BCI games also typically do not “score” the subject in the same way an action or a puzzle game would. This may cause the subject to relax more when using the simulation and provide better results.

### E. Puzzle Games

Puzzle games require the player to think logically about decisions within a game. This can take time for most players. This makes the puzzle genre ideal for BCI gaming as most BCI games have significantly slower gameplay than their non-BCI counterparts. BCI puzzle games typically take the form of existing puzzles and tweak them to allow for accurate BCI control. An example of this is presented in [53]; a game that allowed a player to use the P300 evoked potential and motor imagery to control a game of *Tetris*. The *Tetris* game was used to test if the P300 could be used to help children with attention-deficit and hyperactivity disorder (ADHD). The objective of *Tetris* is to complete full, solid horizontal lines of boxes on the gameplay space. When you make a line, it disappears and all the blocks shift accordingly. If you let the blocks reach the top of the *Tetris* board, you lose. The player's task is to simply position the blocks so that they would make a full line of blocks across the screen (this is quite challenging even for a non-BCI game) [54].

Three versions of the game were developed, each varying in the way they used BCI to control the dropping of the blocks. The first game type used P300 to simply select the correct piece to be placed within the *Tetris* screen (Fig. 9). The piece would automatically be placed in the correct position if the player had chosen correctly. The player had to choose out of the 16 possible

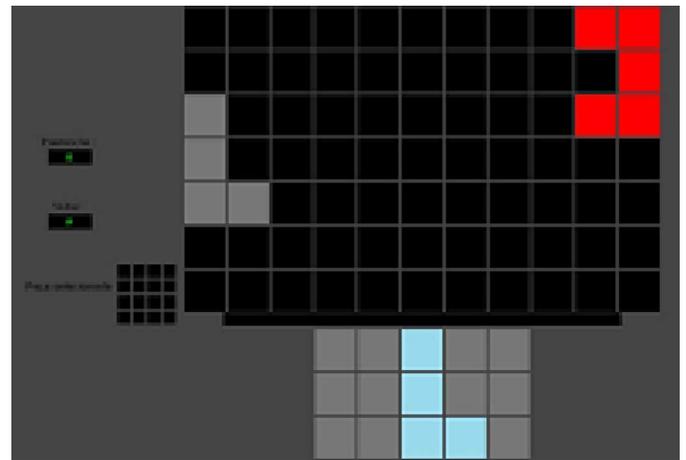


Fig. 9. The game board used for the P300-based *Tetris*. The user selects the target piece to be selected at the bottom of the screen [53].

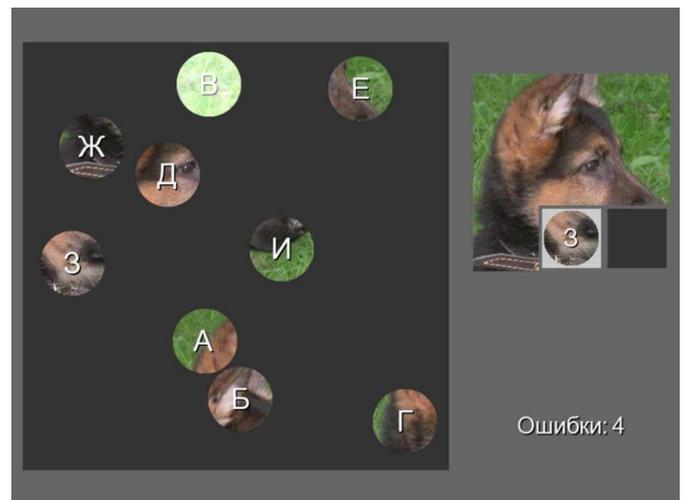


Fig. 10. The BCI puzzle gameboard. The left of the board being filled with moving puzzle pieces and the area selected in the puzzle being shown in the small picture to the right [55].

*Tetris* pieces by selecting one from a small selection window. Each piece was shown within the selection window and flashed for 100 s, then before the next piece was shown there was a break of 200 ms [called the stimulus onset asynchrony (SOA), the interval between the onset of two consecutive stimuli]. To increase the event's perception, each shape was a different color. Also, to help the user, the target piece was shown on the game board in gray. When the user picked the correct shape, it was rotated and positioned in the correct way. This version of the game does not include many gameplay elements of the original game, with the player's only objective being to choose the correct *Tetris* piece to fit within a space on the screen. This change made the game significantly easier for the BCI user. The second version of the game allowed the user to control the block's rotation and position before the *Tetris* piece fell. The player was given a randomly selected block out of the 16 possibilities and had to first rotate it to the required axis out of the four options, then to choose its positioning to fall out of the four possibilities. This version of the game is a lot more true to the classic *Tetris* gameplay. The third version of the game allowed the players to

choose the rotation of the *Tetris* piece via P300, as in the second version of the game. In this version, the player could also control the piece's position by using motor imagery. This allowed the player to choose a position for the piece to drop and so increased the possible choices the player could make within the game. As the player could change the horizontal position more accurately, this version of the game relied more on the player's gaming skills, rather than the player's ability to make simplistic choices.

*Brain Tetris* is a good example of how an existing well-known and popular game can be modified with BCI control in mind. The game allowed for significant control of a fast paced puzzle game via simple modifications, such as allowing the player to take his/her time when deciding to place a piece using motor imagery (avoiding errors caused by the use of motor imagery). The game also allowed full control of the block's orientation while the piece was stationary and allowed the player time to choose the correct orientation before descending into its position on the game board.

Another good example of puzzle game interaction using BCI is the simple picture puzzle presented in [55]. A picture puzzle is ideal for a BCI game as it allows a player to choose pieces at his/her own pace. This allows the player to concentrate and the BCI to complete its cycle. The game was developed to test if it was possible to obtain accurate results from a P300 BCI if the stimuli are moving. The developers had already made a static version of this puzzle game, the BCI puzzle [56]. The game required players to create a picture using moving circular puzzle pieces. To find the correct puzzle piece, the player must gaze at a certain piece to put it into the puzzle; this choice was detected using a P300 BCI. The game's interface consisted of dedicated windows for the puzzle and pieces. This allowed the player to be shown an area where they would place the piece into the puzzle (via the game highlighting a box from the 9 by 9 grid), then allowed the player to choose the correct piece from the moving pieces (each piece moved on its own individual trajectories). If the player chose the wrong piece for the highlighted area on the puzzle, the error counter increased by one and the puzzle piece was not placed inside the puzzle. The player could win the game by completing the puzzle with all nine pieces placed within the correct areas. The player would lose the game by having an error count of 10. This would result in the game being reset and the player having to start again. The use of scores in the puzzle game supplies the player with onscreen feedback of how they are doing within the game. This is good for players as it encourages them to play better or to replay the game to end the puzzle with a higher score.

BCI puzzle games are typically based upon puzzles that already exist, such as *BCI Tetris* or *Hangman BCI* [57]. The use of popular existing puzzles means subjects are likely to be already familiar with the game's objectives and rules. This allows subjects to concentrate on controlling the game via BCI.

## V. DISCUSSION

### A. Accuracy and Performance Quantification

The accuracy of the controls within a BCI game is extremely important, as precise and responsive controls contribute greatly

to a game's gameplay (they provide the user with all interactions with the game). When attempting to accurately contrast results within genres it was found that the use of different BCI paradigms and differences in subject numbers was too diverse. Instead, contrasting similar BCI paradigms results allowed for more informative analysis of games and the techniques used to control them.

Motor imagery BCI games often provide the user with continuous control of an object within the game world. The player is often challenged to make his/her way around a virtual environment using their own decisions. Most motor imagery BCI games measured how well the player could make accurate, correct decisions within the game. Within motor imagery the average accuracy achieved by a player was 76%, suggesting that players with training can accurately control motor imagery BCIs. This was calculated by averaging the mean accuracy (for all subjects) for each study (studies in which a mean accuracy for all subjects is not provided were not included in this estimate). A correlation was also found between the number of sessions and the accuracy of results. It was found that studies with more than four sessions yielded more accurate results. Yet, within many studies, subjects had prior experience of using motor imagery which may have resulted in mean accuracy difference (other studies often used novice BCI users). The simplicity of the games and their control schemes was also a factor affecting most games' accuracies, leading to significantly better results [58], [59]. This suggests that if simplistic gameplay is used within a BCI game, then the subject is likely to have increased control of the game.

Accuracies within SSVEP games were normally measured according to each player's correct responses to the stimuli. SSVEP games had a high average accuracy of 92%. This suggests that the paradigm is accurate and works well within BCI games. Subjects within SSVEP game trials were given little training in comparison to subjects within motor imagery; within certain trials the subjects learned to control the game and were tested within the same session [27]. This suggests that SSVEP is an excellent paradigm for BCI games (high accuracy and short training periods). As P300 games are typically based upon users making single decisions, it was expected that the accuracy would be quite high. P300 averaged 72% within the five games analyzed. This suggested that the paradigm works well within games, yet SSVEPs may be a better option.

Within biofeedback it was difficult to accurately compare the games' accuracies, as biofeedback games depend largely upon the player concentrating within a certain instance of the game or relaxing within another. Player accuracies were not measured; instead, the player's level of concentration would be monitored and used to show each player's progression in the game. As hybrid BCI games are still in their infancy, papers with hybrid-BCI results and testing procedures are limited. Yet, research into hybrid BCI techniques provides some promising results for the control technique [60].

Overall, the accuracy of SSVEP was the highest, yet motor imagery had a higher average accuracy within games than expected. These results suggest that to gain high levels of control of a BCI game, the game's controls must be simplistic, users must be trained sufficiently to use the paradigm that requires minimal training. These observations highlight the ne-

cessity to improve consistency across testing strategies, BCI setups, and reporting strategies for BCI-gaming studies. Nevertheless, it is not always possible to maintain consistency in setup and participant experience. It is, therefore, recommended that all variables be reported thoroughly so that educated comparisons can be made between studies. It is also recommended that multiple performance quantification methods are reported where possible, including standard gaming performance metrics and standard BCI performance metrics. This can only serve to enhance progress in the field and aid in the development of more advanced BCI games and control strategies. The following section highlights performance quantifiers which should be applied where possible.

### B. Performance Quantification

Conventional games generally measure the player's performance via several different methods, all relating to how well the game is played. A typical performance metric in a game is the player's score which may relate to several different aspects of the game. A player is rewarded with points by completing objectives in a game, then the points add to the player's overall score. The more game objectives a player completes, the higher the player's score will be. Many games reward skilful play with bonus scores and multipliers; these are typically triggered by completing difficult objectives [12]. A player's performance may also be measured by the time the player has taken to complete a certain task. This is typically found in games where the objective completion time is measured. Players often compete for the "high score," which could be the highest amount of points gained in a play session or the lowest time to complete the game or objective. Comparing and contrasting scores between games is ineffective as different games typically have different objectives, gameplay aspects, or control schemes. This also applies for BCI games. Yet, by developing a game using multiple BCI paradigms with the same gameplay and objectives, player score and player performance may be measured accurately in each BCI paradigm.

Traditionally, BCI studies report performance using methods such as accuracy (the percentage of EEG events that is classified correctly); ROC curves, including sensitivity and specificity analysis [58]; and bit rate, in terms of the number of bits that can be communicated by the user in a given time period (e.g., bits per minute [62], [63]). Mutual information [64] is another performance measurement tool. This is a measure of how much information can be gleaned from the control signal (classifier output), when the control signal is a magnitude value reflecting the user's ability to modulate a brain response. For example, a larger value reflects the user's ability and the mutual information between the control signal and intended class of action is a measure of the user's ability, as well as the BCI system's performance. Mutual information can be useful for measuring the information reflected in a continuous control signal. In many cases, it is not always possible to acquire this information because the game may have some random elements, i.e., the game does not dictate what the users should do and when to do it (self-paced control strategies). The user's recorded brain response is, therefore, meaningless when offline analysis is performed on the data. In such cases, other information can be

recorded which does not involve analysis of the EEG data but still reflects the user's ability in the context of BCI. Alternative measures include Fitt's law [65]–[67], the concept of utility and mission time, and concentration time estimation [66]. Fitts' law is important for designers of BCI games because it provides guidelines to designing the interface elements and where they should be placed within the game's design, e.g., those tasks where the user must position an object at or on a particular location on the screen. Another metric, "utility," has been studied with reference to a P300 speller design in [68] and has been formalized as to the expected average benefit for the user over time. This notion is mathematically expressed as the ratio of the average benefit to the user for performing any correct command in the expected interval of time. The BCI user or player's ability to reach the desired target in the shortest interval of time is inversely proportional to the value of the ratio or utility. For the evaluation of the proposed methods, the cost function was calculated as proposed by Rebsamen *et al.* [69]. A cost function has also been used to assess a user's performance when undertaking a task or mission in BCI [67] and could be applied effectively for BCI-game performance assessment. The cost is calculated as a summation of concentration time ratio (CTR) and the mission time ratio (MTR):

$$\text{cost} = \text{mission time ratio} + \text{concentration time ratio}$$

where the CTR is the fraction of time the user has to concentrate to control the game in a specific time window, or to complete a game level or task, and is calculated as:

$$\text{concentration time ratio} = \frac{\text{concentration time}}{\text{nominal time}}$$

where nominal time (NT) is the minimum amount of time required to complete the task. The MTR is the ratio between the total time taken to complete a task (MT) and the nominal time:

$$\text{mission time ratio} = \frac{\text{mission time}}{\text{nominal time}}.$$

In any game, the objective would be to minimize the mission time with respect to the nominal time, as well as minimizing the concentration or effort required by the user. This method may be useful in gaming as it is easy to calculate the nominal time to complete a game task and then calculate the effort required in the player's chosen strategy or path, before subsequently estimating how long the player was required to concentrate given the chosen path. This approach has been applied to assess mobile robotic navigation through mazes and wheel chair control [36],[69].

## VI. RECOMMENDATIONS

There are several challenges that BCI games have yet to address. If ongoing research succeeds in overcoming these challenges, BCI games may, in the future, be regarded as legitimate games, with gameplay challenges and objectives emulating games with conventional control systems. Challenges not yet addressed include the following.

- Adding speed and accurate control to BCI action games: Many BCI action games need to be slow and allow the

player to make slight movement mistakes. However, within most commercial action games, the player is required to react quickly and make split second decisions. BCI control in action games needs to become more accurate and challenge players to test their reactions. This can be achieved by adapting difficulty progressively as well as tailoring gameplay to suit the BCI paradigm.

- The use of visually nonfatiguing BCIs: VEPs involve the use of flashing stimuli to infer a user's intent. The user is required to gaze at one of these flashing or iterating symbols to interact with the system. This may not be suitable for longer play sessions. Motion onset visual evoked potential is a type of VEP that uses visual responses from the dorsal pathway of the visual system, allowing more elegant visual stimuli. It, therefore, could allow the user to play for longer periods of time without becoming visually fatigued [70]. Other approaches which involve exogenous and endogenous auditory-based BCIs may also minimize fatigue and free up the visual channel to observe and attend to interesting game graphics [71]–[73].
- BCI integration within other game genres: BCI control strategies have not been developed for genres such as sport, construction/management simulations, or artificial life games. User interaction within these genres may be different, for example, management simulations require high levels of concentration and logical thinking. This may affect a BCI's performance. Artificial life simulations would also affect user's emotions and would be interesting in the use of passive BCI [74].
- Integration of multiple gameplay types within one BCI game: BCI games tend to keep the gameplay the same throughout the game, which may be because most games are used for testing. Yet, BCI games need to allow players to experience multiple gameplay scenarios within a game. This would allow users to experience and learn how to use BCI techniques within different gameplay situations.

As most BCI games are used to test a paradigm or to train subject's, opportunities to create new BCI-based gameplay have been ignored. BCI gameplay elements could include the following.

- The use of passive BCI to change the game's objectives: Passive BCI allows a system to tell if its users are in a relaxed or agitated state. The creation of a game that makes game objectives easier or more difficult depending on the user's state has yet to be developed. This could also be applied to existing games that allow the player to change difficulty. Some commercial BCI games have elements that involve distortion of controls or environment [75], [76], yet the changing of actual objectives and gameplay elements in a BCI game based on passive control has yet to be substantially developed.
- Creation of more BCI games that use existing titles: Integration of BCI within existing games' titles is growing in popularity as it allows more users to experience BCI, as well as taking BCI gaming to new genres and game types. The games are produced to a much more professional standard by large teams of game developers with substantial financial investment.

- The use of hybrid BCI: Hybrid BCI has been used within several BCI games, albeit within a BCI switch form, allowing only one type of BCI to be used at one time, with limited concurrent use of two or more types of BCI. BCI and traditional controls have also been used via a switch. Within [77], a simple driving game was controlled via BCI, although if the signal quality dropped below a certain threshold, the player would be temporally switched to a traditional control method. The use of this method combatted the issue of low signal quality when using motor imagery to control a game. In games such as described in [28], two BCI types have been used in parallel. This is likely to engage/immerse a player much more and may improve his/her experience as he/she is likely to feel as if he/she has more control over the game, i.e., if both BCI control types can be accurately controlled.
- Cooperative BCI gaming: BCI games typically tend to allow control of the game to only one player or allow two players to compete. A cooperative BCI game could allow two or more players to assist in controlling a BCI game. This could allow one player to control an avatar's movement and another to control its movement speed or vision/targeting. This may lead to improved game performance and immersion. Studies have been carried out detailing social interaction during the use of a simple cooperative BCI game.
- Positive feedback: Another important factor is the consideration of a person's level of ability to control the BCI, and that those who perform poorly may actually benefit from an incorrect belief in their actual performance level [78]. This would imply adapting the control signal based on knowledge of the targets in a supervised manner such that the user thinks he/she is performing better—a method which may help in the initial training phases to improve BCI performance and gameplay feedback to maintain interest while the users learn to control a BCI. Game assistance is common in all games for users with different levels of experience, e.g., novice, rookie, expert, with varying levels of difficulty for the same task: easy, medium, and hard.

## VII. CONCLUSION

Games within BCI are limited only by the control schemes they use. Most BCI games to date have been used for training purposes, or to test a BCI paradigm, and employ simplified gameplay mechanics. Gameplay must be altered to achieve accurate control of the game and to make the game more enjoyable for the player. Within most BCI games, the alterations have meant simplifying the game's gameplay significantly. Gameplay within most existing BCI games involves the player controlling only one aspect of the game (character movement, simple choices, or passively altering the gameplay). Within many studies, users have commented that the use of BCI made these small activities significantly more entertaining (as opposed to when using a traditional input device) [28], [79]. High accuracy results are largely due to the simplicity of the underlying games; if they are applied to most commercial games, they will not work as replacement control schemes.

In order to create entertaining BCI games, we need to examine the gameplay challenges associated with the genre and match the gameplay with appropriate BCI control strategies and *vice versa*. For example, action, RPG, and vehicle simulations genres may not be suitable when the BCI reaction times are very slow, whereas turn-based strategy games, CMS, and puzzle games are perfect for BCI as there are normally no time constraints.

Accuracies within BCI game genres varied significantly and depended more upon the BCI paradigm than the genre of the game, yet similarities within paradigm accuracies were apparent. VEP-based games had, on average, higher levels of accuracy than motor imagery and biofeedback games (Tables I–III). Action games are the most popular BCI game genre. This could be attributed to the fact that traditionally controlled action games are more popular or because the action genre is so diverse. Yet action games are largely an inappropriate choice for BCI games without some adaptation because of their fast paced gameplay.

Game genres within BCI games are quite varied, with puzzle, action, strategy, and simulation game genres being used. Yet, opportunities to test subjects such as athletes within sports games, or the use of an adventure game with VEPs, have not been explored. Overall, gameplay within BCI could be improved, yet the game's gameplay will be limited by the accuracy of the BCI translation algorithm and the player's capacity to provide the desired response. With the use of more accurate and faster BCI paradigms, BCI games could become more involving for the player and also display better results (the player's score and the player's accuracy).

Finally, it is recommended that, as traditional and BCI games evolve, many different variables such as the player's level of BCI control proficiency, the number of sessions a user has undertaken, types of control strategies, BCI setup (including the number of electrodes used), types of assistance, games distractions and environments, along with other variables, should be reported consistently. It is important that BCI-game developers and testers glean and report as much information about BCI-gameplay performance when presenting new gaming concepts and studies. This will enable thorough comparison between approaches, leading to the development of better techniques to improve BCIs, better BCI games, as well as BCI-game interaction strategies for all types of games genres. Categorizing games by genre and specifying which genres work well with particular brain-computer games interaction strategies will help develop the field and allow game developers to engage more in BCI-game production.

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