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S.I. : VR AND AR SERIOUS GAMES

EEG-based BCI and video games: a progress report

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Abstract This paper presents a systematic review of electroencephalography (EEG)-based brain–computer interfaces (BCIs) used in the video games, a vibrant field of research that touches upon all relevant questions concerning the future directions of BCI. The paper examines the progress of BCI research with regard to games and shows that gaming applications offer numerous advantages by orienting BCI to concerns and expectations of a gaming application. Different BCI paradigms are investigated, and future directions are discussed.

Keywords Brain–computer interface · Games · EEG

1 Introduction

Since computers have been introduced into our daily lives, more and more of human activity is intertwined with the digital ecosystem. The means of interaction have been limited, for the most part restricted to manual interfaces such as the keyboard, mouse, or the touch screen. The use of other types of interfaces has been episodic and far from being widely adopted. In present times of escalated computing power, the ubiquitous presence of the computer in the professional and entertainment environments, and evermore economical sensors, brain–computer interfaces (BCIs) are a thriving field of research in the area of human–computer interaction (HCI). BCIs as known today emerged from the brain imaging technology, initially from electroencephalography (EEG), later on expanded by other techniques, primarily used as visualization tools for expert diagnostics in the medical field. Regardless of the imaging technology used to implement it, BCI interprets manifestations of complex brain mechanisms, enabling digital interface between the brain and the computer. Across the spectrum of applications, BCIs are implemented by monitoring and evoking particular signal behavior through stimuli presentation or a mental task. Once detected, the activity is used to issue commands to the computer, which can allow the user to navigate a wheelchair, use a hands-free speller, navigate the file system, play games and much more.

A device, exclusively controlled by human brain activity, was first used in 1964, during a brain surgery performed by Dr. Grey Walter. He connected the "next" button of slide projector to the motor areas of his patient, effectively creating the BCI. The patient was able to switch the slide before actually pushing the button, just by thinking of this activity (Wolpaw et al. 2002). However, it took more decades to develop first working noninvasive BCI. Among the first proposed uses of BCIs were mental disease classification and therapeutics using biofeedback (neural feedback) (Mulholland 1995). BCIs can help people re-gain motor control after stroke or other traumatic brain injuries to re-gain motor control (Daly and Wolpaw 2008; Daly et al. 2009). Although rehabilitation of motor functions is not applicable for patients with progressive brain diseases (such as amyotrophic lateral sclerosis, ALS; multiple sclerosis, Parkinson's disease, or patients with injury in spinal cord), one of the biggest potential uses for BCIs is in their possibility to enable such people to use arbitrary BCI-controlled tools. There

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have been attempts focused on delivering a BCI device for independent home use for persons suffering from ALS (Sellers et al. 2010; Kübler et al. 2005), as well as efforts focused on creation of neural prosthetics and additional feedback channel for disabled people with the use of BCIs (Taylor et al. 2002; Velliste et al. 2008; Collinger et al. 2013; Zander and Kothe 2011).

This paper builds on past findings (Kerous and Liarokapis 2016) that examined EEG-based BCI applications with a potential use in Interactive Virtual Environments in general. However, in this instance all the attention is given to EEG-based video game applications, considering the extent of the research in the field and the numerous benefits provided by such interdisciplinary research efforts.

A general overview of BCIs and games will be provided by segmenting the paper in distinct parts based on the modalities of interaction found in the considered papers. Each subsection provides a revised list of BCI games, as well as a discussion concerning main issues and future directions for modalities in question. Section 2 gives a short overview of previous efforts in describing and surveying EEG-based BCI with relevance for gaming applications. Section 3 summarizes the event-related potential (ERP) interaction modality in games and characteristic electrical signals of interest, while Sect. 4 reports on uses of oscillatory aspects of EEG for use in games. Section 5 provides a general discussion on issues of importance for the future of BCI and Games, and a brief summary and concluding remarks of this paper are given in Sect. 6.

1.1 Importance of EEG

In EEG, the brain activity is detected in the form of weak electrical potentials from the surface of the human scalp. EEG-based devices are easier to set up compared to the invasive alternatives, such as electrocorticography (ECoG), and it is lightweight in comparison with magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) devices (Nicolas-Alonso and Gomez-Gil 2012). EEG signal is obtained by placing the electrodes on the scalp according to the 10–20 system. Introduced in 1957 (Jasper 1958), its name denotes the relative distances between electrodes (10 and 20 %) (Jurcak et al. 2007). The signal from EEG has a very good temporal resolution (Fouad et al. 2015), measurable in the range of milliseconds. However, EEG has poor spatial resolution (in the range of centimeters), and it is not easy to connect underlying neuronal activity with the signal from a specific recording channel. However, in order to be recorded, the signal needs to cross the skull and scalp; moreover, additional noise is introduced from the subject (eye movement, muscle activity), as well as from the environmental disturbances (electronic devices, power line noise). This leads to lot of information being diluted and lost in the background. To improve the signal quality, typically conductive gel or a saline solution is applied to the electrode tips, although specialized dry electrodes can be used as well. Nowadays, the most common imaging technology for use with BCIs is EEG. This was corroborated in Guger et al. (2015), where a year-by-year review of participants in The Annual BCI Research Awards (since 2010) showed 72.5% of studies employed EEG, with earlier years reflecting a similar trend. The same was concluded in a 2013 literature survey (Hwang et al. 2013), where a continuously increasing number of BCI research were noted, especially those employing EEG.

The literature has seen numerous parallel approaches to categorizing BCIs in general. There is little consensus and continuity in these distinct groups of authors. The principal approach to categorizing BCI is to subdivide them into invasive and noninvasive (Berger et al. 2008). In Del R. Millán et al. (2008) and Lécuyer et al. (2008), authors categorize noninvasive BCI as "evoked" or "spontaneous," in Leeb et al. (2007) they are differentiated as either synchronous or asynchronous, and in Kleber and Birbaumer (2005) authors make a distinction between BCIs based on externally triggered actions (exogenous) or user-initiated ones (endogenous), while in Wolpaw et al. (2002) they are regarded as either dependent or independent based on the use (or nonuse) of peripheral neural pathways to establish control. Most prevalent approach is the active/passive/reactive categorization (Zander et al. 2010), where active BCI is controlled directly, consciously and independently from external events. Passive BCIs rely on non-voluntary control for modulating the interaction with implicit information from the brain, while reactive BCIs rely on external stimuli. There are numerous factors to consider when designing a BCI, such as signal processing pipeline, particularities of the required training/calibration session, as well as the approach to establishing control. Although the terminology remains to be clarified, it is clear that not all BCI types are suitable for all use-cases. This is especially true for games, since the requirements depend on numerous game elements.

1.2 Importance of games

The main concern with the BCI system is its capacity to accommodate user expectations and implement a natural interaction. Some of the paradigms of interaction in BCIs are tiring and demanding to the user, whereas games directly depend on user engagement, intuitiveness of the controls, and rely on entertaining, motivating, as well as challenging elements of the experience. This has implications for user recruitment for BCI experiments, as well as for improving the palatability of the BCI experience. Games are characterized by diverse genres, but even more so by multitudes of different rules and mechanics. Given the continuous rise of the video game industry, the tools to develop games (game engines) are readily available, which, to a limited extent support integration of BCIs enabling faster prototyping of BCI scenarios.

Some of the ways, in which the games can help in the research environment, are outlined in Washburn (2003):

1. Games as stimulus to study human behavior
2. Using games to manipulate experimental variables
3. Games as means of instruction
4. Employing games as performance metric

Benefits of BCI games research are also mentioned in Järvelä et al. (2015), such as that games are much more approachable to people, which helps patient recruitment and offers the possibility of using more complex tasks in a controlled environment. It is evident that using games for BCI research provides a beneficial experimental environment, and on the other hand, through further advances in sensors and BCI research, the games will can be enriched by innovative game-play BCIs can provide.

The current state of BCIs is such that some paradigms are very demanding of the user and they divert attention from the events in the game. In order to continue the course to widespread adoption of BCIs, user concerns, as well as performance issues need to be addressed. The first priority is to improve the actual usability and stability of the system. In Gürkök et al. (2014) the authors conducted an investigation of players opinions on control of a BCI game and introduced a set of guidelines for future BCI game development. They accentuate that the user must be able to guess and predict the outcome of their mental effort. Similarly, in the case of BCIs that rely on users disposition, authors note that there should be a meaningful proportionality between the users subjective mental state and the effect it has on the developments in the game. Another notable attempt to establish a framework for the future BCI gaming applications (Gürkök et al. 2012) suggested that the designers should consider three guiding aspects of gaming BCIs: role of Challenge, Fantasy, and Sociality. In summary, the authors suggest a more central role of the user experience in assessing the interface. Similar user-centered approach is encouraged in Loup-Escande et al. (2017), where authors highlight the importance of the perceived usefulness, usability and acceptability when evaluating a BCI game design. Another recommendation is to promote the hedonistic qualities, as well as immersion and presence in the gaming environment.

2 Summary of EEG-based BCIs and games

Building on the previous survey work in the field, this paper will attempt to review of efforts undertaken in BCI research relevant to their application in gaming environments. By analyzing and comparing referenced work in the survey material, and adding recent research a synthesized list of all BCI games is given. The basis of this paper are three survey papers Bos et al. (2010), Marshall et al. (2013) and Ferreira et al. (2014) that examined, to different extents, the use of BCIs in games. A survey paper Bos et al. (2010) was the first to systematize efforts in BCI and games. Although the authors did not set out to survey exclusively EEG-based gaming BCIs, only one of the listed papers (in total 36) used a non-EEG device. Authors noted that the BCIs are a weak replacement for traditional input, and that a big gap needs to be bridged between games in research and commercial games. In the 2013 survey (Marshall et al. 2013) a trend of increasing use of games for BCI research was highlighted, while noting that the main limitations of such system are reflected in the limited control schemes that are employed. Here more emphasis was given to game genres and their role in defining the paradigm of choice for accomplishing the interactions. However, the use of the game genres to orientate a BCI game is of questionable importance, since they are not unambiguously determined, are more fluid, and tend to overlap depending on the mechanics of the game. Nevertheless, the authors bring forth the inconsistency of performance metrics in reported publications, which is still a noticeable problem. They noted a variety of genres present in reviewed studies and that researchers show no clear preference in genre. In total, they listed 54 papers of interest, out of which there was only one employing a non-EEG system. In Ferreira et al. (2014) the authors provided a list of 35 publications featuring BCI games. Different considerations were examined when designing a BCI game, and a set of recommendations on design choices based on genre-specific mechanics was presented. All three papers contained a list of publications featuring BCI games, which served as the basis for this paper. In total, the referred papers yielded a list of 125 publications. After removing duplicate instances the total was brought to 71. This list was further narrowed down by eliminating items that would fit the following exclusion criteria:

1. Items that did not use an EEG-based BCI
2. Items where control was not established in a video game using any type of digital display (such as playing a pinball machine, or navigating a drone)
3. Items with missing publications, or items featuring the same BCI game designs in two or more publications
4. Items showcasing theoretical designs or offline studies
5. Items featuring simulations or visualizations and other implementations that did not orient a user to achieving a specific goal, nor gave video game feedback on the users performance (keeping score or time record) were removed

6. Items that included animal BCI

After comparing against these exclusion, criteria the total number of papers was reduced to 59. By inspecting the literature further, additional items were added and the total number was brought up to 74 items. Figure 1 shows the number of published papers year-by-year, while Fig. 2 illustrates the contribution of the different interaction modalities (to be discussed in the following sections).

The decision to choose a specific modality to establish control in a game is not trivial, and not all modalities of control are suitable for every task (Lotte et al. 2012). In the following sections, all interaction modalities are critically assessed with regards to their use in the field, and recent discoveries that drive the development of the interface. Most instances of individual games of different modalities shown in the tables will not be reviewed. Instead, a more general approach to elaborating the role of the control paradigm in question, as well as research of relevance concerned with its advancement, is brought forth to consideration.

3 Event-related/evoked potentials

Event-related potentials (ERPs) are electrical potentials generated by the brain that are related to specific internal or external events (e.g., stimuli, responses, decisions). They can provide information about a broad range of cognitive and affective processes (Luck 2014). ERPs provide us with an insight into sensory and cognitive processes. Event-related potentials are numerous and are usually referred to as ERP components. In the most common ERP naming convention, the letters P (for positive) or N (for negative) are used to indicate the polarity of the component, followed by a number indicating the peak latency of the waveform. Using the polarity to label the component is problematic, because any given component will produce a positive potential on one side of the head and a negative on the other side which will also depend on the location of the reference electrode. Furthermore, ERPs cannot be read directly from a specific potential spike in the EEG signal, since the spike may or may not represent a specific component (such as P300) and would be a combination of underlying concurrent potentials (Luck 2004). ERP analysis is primarily focused on monitoring the time domain of the signal in a specific interval after the stimuli has been presented. Experimental design as well as the appearance and behavior of the triggering stimuli are crucial factors of a functioning ERP-based BCI. The stimuli presentation specifically has been steadily changing, especially in the gaming implementations. These developments are marked with a tendency toward seamlessly melding the stimuli in the gaming context, with the goal of being more intuitive and visually appealing. The presence and attributes (amplitude and latency measures) of the component of interest for a specific experimental conditions can be validated through offline analysis of averaged intra-subject and inter-subject waveforms. This validation is mostly absent from the papers considered here, which presents a problem for replication and future research. ERP modalities are well suited for a number of in-game tasks where a discrete command can be issued, such as arcade-style games or puzzle games. Depending on the control scheme, this modality can be integrated in a continuous control paradigm such as in racing games or games that require navigation. Although its use depends on the design of the game, ERP modality

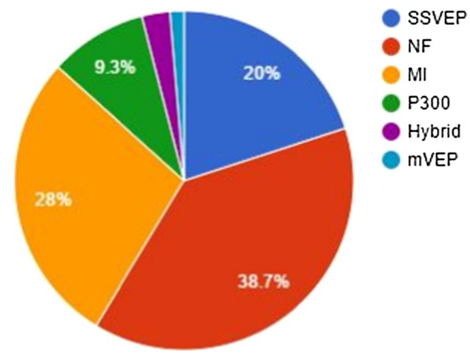


Fig. 2 Ratio of different modalities used for BCI gaming implementations

Fig. 1 Overview of published BCI games papers per year

is best suited for non-real-time control such as turn-based games where a delay prior to issuing a command does not play a significant role in determining the outcome, especially if the triggering stimulus is seamlessly embedded in the user interface. Refer to Table 1 for a list of papers featuring ERP and Evoked Potential-based BCIs.

3.1 P300 event-related potential

P300 represents a positive peak observed in the EEG that represents cognitive processes of stimuli evaluation (Ramadan et al. 2015). The characteristic of the P300 peak is that it is much larger for infrequently occurring stimulus categories than for frequently occurring stimulus categories. It is most often observed in the oddball paradigm, in which the stimuli that break from the preceding ones elicit a larger P300 amplitude than the standard stimuli. The process of detection of a command signal requires a classifier to be trained on a set of recorded epochs in the EEG signal obtained during the distinct training session.

Although games that utilize the P300 are not numerous compared to other modalities, P300 does offer some advantages. It is very robust considering it does not require user training and can be evoked as a response to auditory or tactile stimuli. However, to detect the control signal the user has to be presented by the appropriate stimuli first, which can have a distracting effect, especially in a fast-paces game environment. In a study (Guger et al. 2009) that assessed performance of 100 subjects, it was shown that 72.8% of participants were able to spell with 100% accuracy, while less than 3% of them were unable to spell any character correctly.

First used in a study implementing a speller application (Farwell and Donchin 1988), this modality has undergone significant research and has been established as a staple of the BCI interaction inventory. The stimuli in this modality are usually arranged in a grid of elements, which is re-purposed depending on the game in question. For example, in the 2009 implementation of P300 speller for an arcade-style game (Finke et al. 2009), the level is laid out on a 28×18 grid, and the character moves to a square by attending to it.

In a review (Kaplan et al. 2013) of the use of P300 in context of games, the authors highlighted some of the potential reasons why we are not seeing more P300-based games. One of the reasons stated, was that the users expect a continuous control of movement, which is not feasible with P300 that only enables selection from a predefined set of commands. Another problem is that the user is required to count the triggering events which distracts the user from the game conditions. In spite of these difficulties, there are excellent examples of BCI games, such as a user-friendly game called Brain Invaders (Congedo et al. 2011). The researchers were able to implement an arcade shoot-em up game where the user destroys the particular enemies by attending to them. Furthermore, it is important to note that the classifier calibration was seamlessly integrated into the game. An interesting puzzle/action hybrid (Ganin et al. 2011), where user attends to particular free-floating segments of the image requiring assembly, has shown that P300 presentation modality stands even if the stimuli is moving. Throughout the years, P300 was used as a control modality for Second Life (Edlinger and

Fig. 3 Attention training (Rohani and Puthusserypady 2015)

Table 1 ERP/EP BCI games

Paper	Electrodes	*N*	Modality
Finke et al. (2009)	NA	11	P300
Ganin et al. (2011)	6	12	P300
Congedo et al. (2011)	31	4	P300
Edlinger and Güger (2011)	8	NA	P300
Maby et al. (2012)	9	2	P300
Angeloni et al. (2012)	8	5	P300
Rohani and Puthusserypady (2015)	3	6	P300
Vidal (1977)	5	NA	SSVEP
Martinez et al. (2007)	6	1	SSVEP
Moore Jackson et al. (2009)	2	24	SSVEP
Hakvoort et al. (2011)	32	17	SSVEP
Vliet et al. (2012)	14	23	SSVEP
Kapeller et al. (2012)	8	NA	SSVEP
Kos' Myna and Tarpin-Bernard (2013)	14	30	SSVEP
Legény et al. (2013)	8	12	SSVEP
Parafita et al. (2013)	12	5	SSVEP
Chumerin et al. (2013)	8	20	SSVEP
Po-Lei et al. (2014)	4	3	SSVEP
Ali and Puthusserypady (2015)	3	11	SSVEP
Wong et al. (2015)	4	20	SSVEP
Koo et al. (2015)	8	3	SSVEP
Marshall et al. (2015)	12	15	mVEP

Güger 2011), competitive Connect Four game (Maby et al. 2012) proving it can be re-purposed for numerous uses. P300 is also an effective indicator of attention since the amplitude of the evoked response is correlated with it, and in a study (Rohani and Puthusserypady 2015) it was effectively used for attention training (see Fig. 3). The task consisted of a 4x4 matrix similar to the P300 speller proposed by Farwell and Donchin. The pilot study concluded that there is significant potential for ADHD treatment using the system. Since attention and workload are tied together and make up an indicator of the subjects performance in sustained attention, the P300 was shown to be used for the assessment of workload within a game environment where the user was charged with a simple piloting task (Causse et al. 2015). A P300 component P3b was shown to reflect the depletion of cognitive resources allocated to processing of instructions. Considering the graphic complexity of modern games, it is of interest to establish the dependence of the P300 modality on scene complexity. This was tackled in Amaral et al. (2015), where the authors found that the P300 can be detected even on a single trial and is robust with respect to the scene complexity. Demonstrating the possibility of incorporating other interaction devices along with a BCI, in Bayliss and Ballard (2000) the authors used a head-mounted display (HMD) and steering wheel controller for driving in a virtual environment. There the triggering stimuli was presented in the form of traffic lights, where P300 was detected as reaction to a shifting light. Here, the authors demonstrated that P300 can be effectively evoked in an immersive environment, and that it can also be harnessed for control even when a person is engaged in a parallel motor task (turning the wheel), which generates muscle artifacts.

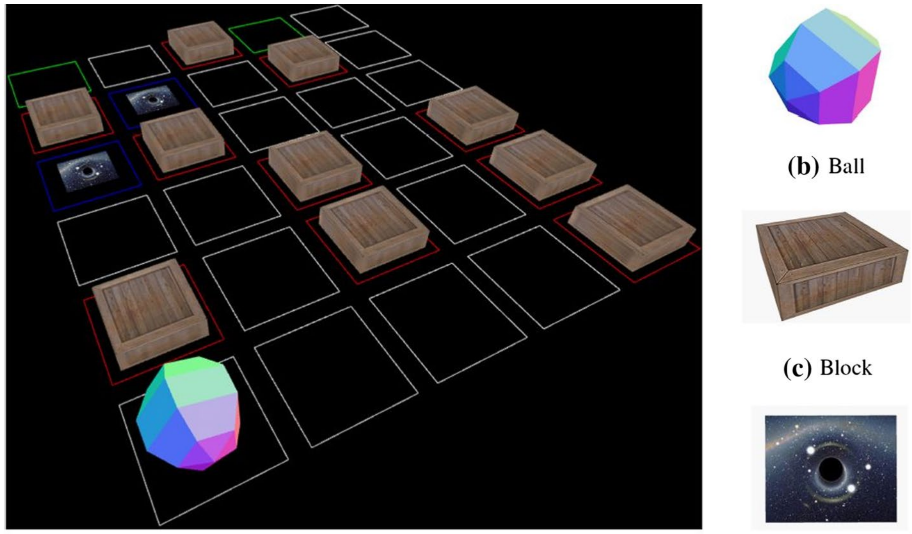
3.2 SSVEP

Steady-state visually evoked potential (SSVEP) is a control paradigm where the user is presented with a flashing graphic of high contrast typically on a computer monitor. When the subject focuses their attention on such an object/symbol, the signal that matches the frequency of the stimuli oscillation can be detected over the primary visual cortex of the brain (Picton 1990). Although this methodology relies on evoking responses to attended stimuli, the detection of the response is conducted by looking for the matching frequency (and its harmonics) response in the occipital region. This makes it less prone to artifacts than other modalities, since the attended frequency becomes predominant and easy to detect. As early as 1977, Vidal (1977) designed a BCI-controlled game that used checkerboard patters to indicate movement direction and facilitate interaction within a maze environment, where the user was tasked to navigate out of it. The performance of SSVEP BCI was rigorously examined in the study that tested the performance of 106 conference attendees (Allison et al. 2010), where it was shown that although most of the participants were able to control it, different stimulus frequencies produced different levels of brain response between participants. Another concern cited by the authors is light pollution from outside light sources. It is important to note that there are other limitations to the use of SSVEP paradigm. The biggest problem in the SSVEP-based BCI is the fact that the band of easily detectable frequencies is very limited, so the number of controls that can be coded by different frequencies is also limited. Other problems were assessed in Zhu et al. (2010). In this review of 57 papers on SSVEP, the authors noted that although the SSVEP can be presented with frequencies of up to 100Hz, stimulation frequencies in the low- and medium-frequency bands have been more often applied than those in the high-frequency band, even though the latter offer higher levels of comfort and safety. Similarly, most of the SSVEP implementations in games used the standard monitor to present the stimuli and hence have used only lower frequency of the flashing stimuli. The properties of the stimuli (color, display modality, frequency) heavily influence the performance of this BCI. A number of interesting papers confirm the viability of SSVEP in the gaming context. In a pilot study proposing the use of SSVEP for clinical purposes (Parafita et al. 2013), the gaming task consisted of flashing stimuli embedded in the virtual scene featuring a spaceship. A very short training time of 2 minutes was found sufficient to establish meaningful control.

To tackle the detrimental effects of workload on the efficacy of the interface one study (Legény et al. 2013) designed and evaluated a context-sensitive command approach, where commands that have no effect on the outcome are removed, to simplify the interface and reduce the workload. Demonstrating the potential use of the SSVEP BCI for attention Training in ADHD a study (Ali and Puthusserypady 2015) tackled the issue using a 3D virtual game with distractions, confirming yet again the possibility of embedding the SSVEP stimuli within VR without detrimental effect to the accuracy. A proof-of-concept study (Koo et al. 2015) (see Fig. 4) tested the efficacy of the SSVEP paradigm in a virtual scene viewed through an HMD. The results were compared to the performance in the same game using the computer monitor, and results imply an improved information transfer rate attributed to lesser susceptibility to visual distractions when using HMD. Alternatives to a visual presentation of stimuli are also possible by using other senses such as touch (steady-state somato-sensory evoked potential) and sound (steady-state audio evoked potential).

3.3 Other ERPs of interest

The stimuli used in the early experiments with BCIs were intentionally simplified to elicit only a specific potential spike. However, other underlying components of the



(a) Map (b) Ball (c) Block (d) Warp-hole

Fig. 4 VR maze game using HMD (Koo et al. 2015)

ERP can also be detected simultaneously and this provides an opportunity to improve the detection efficacy by adapting the behavior of the triggering stimuli. This was explored in a study (Bianchi et al. 2010) that used a standard speller application to investigate the role of the other ERP components. These results suggest that the N100 potential can be triggered as well, to improve classification performance. Another interesting example of how different stimuli can be stacked for combined effect used a standard P300 speller stimuli presentation, where letters were replaced by images of human faces (Kaufmann et al. 2011). The rationale behind this lies in the fact that there are ERP components that are evoked in response to seeing a face (such as N170 and N400f), and therefore the P300 speller can easily be adapted to other triggering stimuli or enriched to improve the classification. It is also encouraging that the use of the face-sensitive N170 component was validated in an offline study of a game-like task using a commercially available EEG device (Lissa et al. 2015). Similarly, in another study, the authors successfully employed an animated smiley-face emoticon in such a way that that the animation of an unattended stimuli could not be noticed (Jin et al. 2014), thereby reducing the likelihood of a false positive appearing in the signal. Another recent addition to the available interaction modalities is the motion-onset VEP (mVEP) ERP which is evoked when the focused stimuli exhibits a movement. The mechanism of mVEP was first established in 1992 and found to rely on the N200 and P200 components of the ERP (Kuba and Kubová 1992). It was first assessed in an offline analysis of a 6x6 matrix of stimuli that consisted of white icons with a sliding vertical red bar (Guo et al. 2008), which proved it can be used as a N200/P200-based speller application. In the gaming context, mVEP was assessed as the control modality in three computer games: action game (virtual environment shooter), puzzle game (ball drop path estimation) and sports game (Bowling) (Marshall et al. 2015). Further studies have shown that it can be robustly detected even when buttons were overlaid on the top of the complex graphical background in five distinct commercial games (Beveridge et al. 2016). Another interesting innovation in the way the stimuli is encoded is the codebook VEP (cVEP), where the stimuli do not follow the fixed frequency flashes as is the case with SSVEP, but flashes according to a pseudo-random binary sequence (Bin et al. 2009). This methodology promises to expand the number of different stimuli, since the span of usable flashing frequencies in a SSVEP-based system is restricted. The cVEP has proven its validity to control a virtual agent in a 3D kitchen scenario for navigation and selection tasks demonstrating its resilience to the complexities of the virtual environments (Riechmann et al. 2016). Apart from the aforementioned features of ERP, other types of evoked potentials have been shown to be feasibly implemented in a game context. One such example is the Slow Cortical potential (SCP) which can be evoked from 300 ms to several seconds after stimuli onset (Strehl et al. 2006). Used mostly for the medical treatment of ADHD, the user is presented with a game-like task. where through reinforcement learning he manages to modulate this potential. Although not widely employed outside the therapeutic context, it is worth considering since it is regarded as reliable for a wider population (Mayer et al. 2013). Yet another intriguing ERP is the error-related negativity (ErrN or ERN). It is evoked the moment the subject perceives the error in a task (Falkenstein et al. 2000). Detectability of such potentials was examined in a game-like task, and results show that there is possibility to differentiate among different ErrN triggering events (Spüler and Niethammer 2015), which holds promise for the field (e.g., the detected errors can be used to adapt the challenging aspects of a game).

4 Oscillatory EEG

Event-related methodologies suffer from the dependency to outside stimulus to occur before a mental command can be issued. This prevents the user to initiate a command at will and hinders the intuitiveness of the interface. On the other hand, oscillatory-based BCI implement control by continually monitoring the frequency domain of the signal, thereby giving a continuous read out of brain activity. This rhythmic brain activity is constantly detectable and features in different wave bands: alpha (7.5–12 Hz), beta (12–30 Hz), gamma (31 Hz and above), delta (0.5–3.5 Hz), and theta (3.5–7.5 Hz) (Ramadan et al. 2015). The classifiers are used to distinguish between few classes based on either intensity of the band of interest or the lateralization of it (in the case of Motor Imagery). BCIs that monitor these oscillatory aspects of the signal establish control explicitly (such as in Motor Imagery) or implicitly through EEG signal monitoring of physiological and behavioral processes.

4.1 BCI for affective interaction and neurofeedback

EEG monitoring can be performed in the capacity of physiological recording, where it becomes an indicator of user state. The body of the work done in BCI games that leverage the oscillatory qualities of the signal can be distinguished into ones implementing neurofeedback(NF) and those that use it to establish affective influence on the game. Summarized list of BCIs employing this approach can be found in Table 2. Affective gaming refers to the games in which the players behavior directly affects the game objectives and game-play by recognizing the emotional state or mood, in order to alter the progress of the game (Kotsia et al. 2013). Highlighted in Mühl et al. (2014) are some of the problems in designing and evaluating such interfaces. NF presents one of the earliest forms of brain–computer interaction, which is concerned with representing the neural activity to the patient in clearly understandable way (a bar showing the intensity of the effort), with the aim of training the user to modulate it (Huster et al. 2014). Repeated modulation of brain activity in this has been shown to be an effective therapeutic tool (normalizing brain activity to influence symptoms), performance tool in healthy participants (e.g., meditation training), and as an experimental tool to examine neural events in the context of cognition and behavior (Enriquez-Geppert et al. 2017).

Unlike other modalities, the bulk of the authors conducting research in NF and affective-based interaction have reported using consumer-grade EEG devices. In total

Table 2 Oscillatory BCI-based games

Paper	Electrodes	N	NF/affective
Palke (2004)	1	NA	NF
Shim et al. (2007)	4	NA	NF
Ko et al. (2009)	1	20	NF
Yoh et al. (2010)	1	NA	Affective
Wang et al. (2010)	1	5	NF
Su, Wenyan, and Qiqian (n.d.)	1	NA	NF
Coulton et al. (2011)	1	22	NF
Bernays et al. (2012)	14	NA	NF
Liao et al. (2012)	3	10	NF
Carofiglio and Abbattista (2013)	14	12	Affective
Gilroy et al. (2013)	32	15	Affective
Mercier-Ganady et al. (2013)	16	8	Affective
Laar et al. (2013)	4	42	NF
Thomas et al. (2013)	10	5	NF
Yoon et al. (2013)	1	42	NF
Joselli et al. (2014)	1	11	NF
Khong et al. (2014)	4	3	NF
Liu et al. (2014)	14	3	NF
Friedrich et al. (2014)	NA	NA	NF
Wu et al. (2014)	1	5	NF
Shenjie et al. (2014)	4	4	NF
Muñoz et al. (2014)	NA	NA	NF
Liarokapis et al. (2015)	1	30	Affective
Heidrich et al. (2015)	1	NA	NF
Chouhan et al. (2015)	6	10	NF
Lim et al. (2015)	14	NA	NF
Muñoz et al. (2015)	1	NA	NF
Ewing et al. (2016)	2	10	Affective
Park et al. (2016)	1	5	NF

20 out of 29 presented papers used either Emotiv EPOC our Neurosky EEG devices, which would indicate that the device performance or electrode setup for such uses is of less significance. Considering that this type of game studies is relatively novel, there needs to be a systematic approach to conducting such research. The benefits and challenges of game user research conducted in the context of physiological assessment are outlined in Nacke (2015). For a systematic approach, the authors stressed the importance of proper methodology that would take into account the background information of the user (demographics, skill level), the proper understanding of the meaning of the measured values (understanding the theoretical constructs), and importance of taking into account the environmental variables. In the 2013 review of EEG for use as an evaluation method for HCI (Frey et al. 2013), the authors elaborated on the different measurable constructs as interpretation of the user state. For instance workload, attention, vigilance, fatigue, emotions (based on Valence/Arousal), engagement, flow, immersion

and recognition of the user errors were assessed as feasible indicators of user experience.

There are many examples of offline research in the recent years that used EEG as a physiological measurement, the bulk of which was conducted with the convenience offered by commercial BCI devices, since they fit the real-world gaming environment in a less obstructive way. In one case, authors demonstrated that information generated in this manner can be overlaid over GUI elements to represent the user experience associated with specific choices in the program (Cernea et al. 2013), which can also be re-purposed for gaming applications. Another interesting example is the research performed to generate heat maps of in-game user state (Sivanathan et al. 2014), which offers another layer of potentially interesting information for use in a game design pipeline. Although implemented in an offline environment, it is feasible to consider integration of such mechanisms as a background activity to be used as non-time-critical supplementary information. Other investigations are also possible, such as assessing the impact of specific game events in horror games (Vachiratamporn et al. 2013), examining the intensity of the experience during game-play (McMahan et al. 2015b), and in a general sense to weigh the potential benefits of the different game genres to improve cognitive performance (Mondéjar 2016). The state of flow during game-play was examined in (Berta et al. 2013), the workload in Teo et al. (2015), and task engagement and arousal in McMahan et al. (2015a).

The online, real-time assessment and feedback, however, is of prime interest for the BCI gaming applications, since the interface becomes a parallel mode of control of the totality of the gaming experience. These online EEG approaches are not novel and have been present for decades in limited capacity in the form of NF. Through the session, the users are shown the representation of their neural activity with the purpose of establishing reinforced learning, eventually enabling the users to modulate their own neural activity. Through multiple sessions, real impact on the user's behavior can be achieved. NF, therefore, leverages aspects of EEG as a physiological measure with the sole purpose of giving a direct representation of the EEG activity to the user (Huster et al. 2014).

Some of the examples include, a serious game employing NF training for treatment of Autism (Friedrich et al. 2014), game-based monitoring of sustained attention for ADHD treatment (Muñoz et al. 2015), and an adaptive version of the Tetris game (Ewing et al. 2016). A noticeable trend with NF is to change the behavior of the gaming environment as a response to the brain activity, instead of relying on a simple indicator bar. One sophisticated example varied the number of the characters present in the scene according to EEG-based estimation of the amygdala activity (Cohen et al. 2016) (see Fig. 5). Closely associated with the NF

Fig. 5 Biofeedback-based scene complexity variation (Cohen et al. 2016)

approach is the recent research in EEG and art. Instead of presenting the brain activity using simplified visualizations, researchers explore different and more engaging presentation schemes. In Gurkok and Nijholt (2013) several use-cases are considered such as Audification, or representing brain activity through sound or animation, where the activity can be used to alter the behavior of visualisations or interactive art installations, and control of artistic instruments. Several examples of such possibilities are emerging, especially considering the ease of use of the commercial BCI devices. In Pike et al. (2016), the authors used an EEG BCI to adapt the progression of a film. In Yan et al. (2016), it was harnessed to adapt a performance-art installation in VR, and in Parenthoen et al. (2015) it was used to modify the real-time rendering of a fluid simulation. These examples of EEG in art hold relevance for the future of the BCI and games, since they indicate favorable directions with regard to the aesthetic aspects of the user experience.

4.2 Motor imagery

Another invaluable tool in the BCI control modality toolbox is motor imagery (MI). MI is a special case of NF, where the subjects imagined movement can be detected through monitoring the oscillatory activity in the Mu rhythm, and then be used to facilitate navigation and control. A summary of MI-based games can be found in Table 3. MI modality does not depend on outside-initiated stimuli to facilitate signal detection, although certain stimuli presentation is used in a training process prior to the control session. However, if there is movement occurring during BCI operation, the muscle artifacts would render the interface unusable in most cases; hence, the user is instructed to sit still. During the MI calibration session, usually a training protocol is used, where a person is instructed to imagine limb movement successively to obtain training data. The user is given a visual

Table 3 MI-based games

Paper	Electrodes	N
Müller-Putz et al. (2007)	5	10
Wang et al. (2007)	NA	NA
Krepki et al. (2007)	128	NA
Scherer et al. (2007)	3	3
Bai et al. (2007)	29	9
Oude et al. (2008)	32	15
Zhao et al. (2009)	5	4
Wei (2010)	32	1
Coyle et al. (2011)	24	3
i Badia et al. (2011)	9	5
Scherer et al. (2011)	NA	NA
Lopetegui et al. (2011)	4	4
Bordoloi et al. (2012)	2	13
Kreilinger et al. (2011)	6	10
Hasan and Gan (2012)	9	5
Li et al. (2013)	6	2
Leeb et al. (2013)	5	14
Bonnet et al. (2013)	16	20
Ang et al. (2015)	27	11
Coyle et al. (2015)	3	15
Vourvopoulos et al. (2016)	8	13

cue, indicating which movement to imagine. Although this control modality can be used independently of any user feedback, recent research has shown that giving context to the imagined movement by using 3D models of hands in a virtual environment can help a person perform better and improve training outcomes as well.

This is why this paradigm has seen extensive use as assistive technology with persons with various degrees of motor impairment. Indeed, one of the main roles for games controlled by MI-BCIs nowadays is providing restoration of movement in patients suffering from neurological conditions such as post-stroke state (Ang et al. 2015). Effectiveness of the demanding training that MI-BCIs incorporate can be improved by using protocols that are contextually relevant and take into account the need for maintaining user interest during the session (Ryan and Deci 2000). In a study of MI control (Guger et al. 2003), where 99 participants were tested in classification accuracy. In a two-class system, 20% of the users achieved the 80% accuracy after 20–30 min of training, 70% achieved 60–80%, while 6.7% saw marginal discrimination between classes. Coyle et al. (2011) developed a simple spaceship game for MI training, which was later on modified to include audio cues (McCreadie et al. 2012). The BCI user needs to avoid contact of a spaceship with asteroid by performing left/right hand MI in order to move the spaceship into desired direction. The timing of the stimuli is based on Graz approach. However, the training does not consist of clear instructions on which hand movement should be imagined. Moreover, the game contains distractions (shooting stars and asteroid-like objects that are irrelevant, other graphics, sound, etc.) that cause further cognitive processing in the users. The movement of the spaceship is continuous through the task course, and the synchronization of event timing (asteroids) with Graz protocol is not obvious for the user, creating a more game-like experience. Another effort to make MI-BCI more engaging and its use more natural is presented in Li et al. (2013). The idea of having a competitive mode in a multi-person BCI system is presented in this study. A racing game for two persons was developed and prototyped with two subjects. Authors suggest that competitive mode could be used as a motivational boost in BCI systems, for example, in the training sessions. Separation of classes from the EEG signal can be challenging task, even in the case of two classes. In Coyle et al. (2015), authors tackle this MI-BCI limitation with multi-button controller named "CircleTime." Two classes of MI can be further separated into six different options of control. This is achieved by having two rotating circles, each containing three buttons. In order to select an option, users need to perform MI of left hand or right hand, in order to choose a command from first or second circle, respectively. Feedback on the MI task is provided through raising bars. After selected imagery is achieved and recognized, the rotation of the circles is stopped, choosing the button on current selection. This controller was used for control of an action game. Enrichment of motivation and engagement in BCI systems can also be achieved with multimodal feedback. For instance, Vourvopoulos et al. (2016) developed a rowing game called NeuRow and made use of both visual presentation and tactile feedback. Participants of this study received a handle for each hand with vibrating motors inside. A training protocol based on Graz-BCI was developed; however, the feedback at this stage employed both senses, i.e., haptic and visual presentation of participant's successfulness. The subsequent task in a rowing simulator composed of navigating a boat freely with the goal of collecting as many tokens as possible. Such task is therefore self-paced from the participant's point of view, and although there are events to be followed, participant alone sets the pace for the cruise. Stepping from the arrow-based Graz MI feedback to more immersive training environments has been shown to have positive influence on accuracy in MI-BCI training than Graz approach (Pineda et al. 2003). NeuRow (see Fig. 6) study shows that adding tactile feedback is helpful for the activation of motor areas in the brain, creating more distinct patterns for MI control. Results from the questionnaires indicate lower physical and temporal demand in comparison with the mental demand, which reinforces the utility of MI in stroke rehabilitation programs. Another study that used immersive VR for MI training and tasks specifically designed as a tool

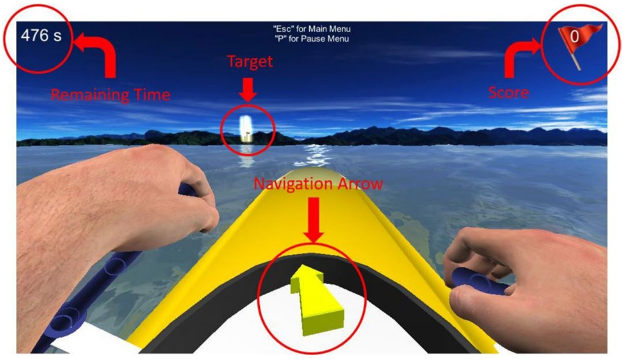


Fig. 6 MI-based NeuRow game (Vourvopoulos and i Badia 2016)

helping with motor function restoration in patients after stroke, was done by Vourvopoulos and i Badia (2016).

4.3 Hybrid interfaces

Most of the research into BCI and games so far has been conducted on a single modality of interaction, that is to say that BCI was used as the only channel for communication. Considering that the performance of such implementations depends on the amount of noise in the environment as well as the degree of users movement, this aversion is understandable. However, If BCI is to become an ubiquitous gaming interface it is of prime concern to examine these approaches, and find ways of designing the games that would leverage the benefits they provide, especially considering that most of the end users would not be likely to sacrifice the comfort and convenience of interfaces they are already used to. Additionally, when there is a possibility to enrich the interaction with other inputs (such as an eye tracker, or another biofeedback channel), the benefits would mitigate some difficulties implementing an exclusively BCI game. Hybrid BCI is defined in Allison et al. (2010) as pure hybrid BCIs that combine two or more BCI paradigms, physiological hybrid BCIs, which combine a BCI with another physiological signal, or mixed hybrid BCIs, which combine a BCI with non-physiological input (see Fig. 7). Another opportunity that has not been sufficiently explored is using present BCI modalities with touch (Erp and Brouwer 2014)- or auditory-based stimuli (Vos et al. 2014). While every BCI interaction paradigm holds merit for gaming applications, there are numerous advantages of using multiple paradigms in a single implementation. When input from multiple paradigms is incorporated in the design, this interaction system is regarded as a hybrid system. In a survey of 55 journal articles on the topic of hybrid BCIs (Banville and Falk 2016), it was found that in most cases hybrid BCIs were used to improve accuracy and to provide additional control signals. Multimodal control was also established through an eye tracker and an SSVEP BCI (Kos' Myna and Tarpin-Bernard 2013). The authors concluded this to be a well rounded control modality since it solves the problem with eye trackers where unintentionally attended items are mistakenly selected. In our survey, there were only two examples of pure hybrid approaches implemented for BCI games (see Table 4). Physiological hybrids are also episodic, while mixed hybrids that feature multimodal interactions are becoming more common.

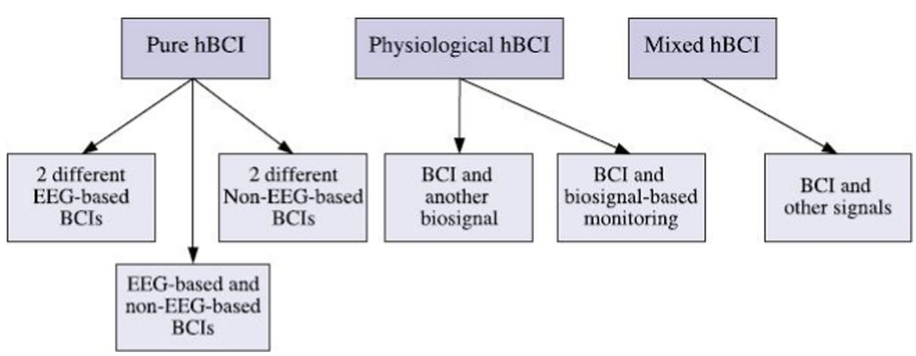
5 Discussion

Although there are many branches of the research community actively employed in BCI research, there remains a dose of skepticism with regard to the performance of EEG BCIs. Lécuyer et al. (2008) examined the implications VR has for BCIs and stress the difficulties in designing a BCI game, and the problem of real-world gaming implementations, which they ascribe to the immaturity of the interface for widespread adoption. Similar position is held in Ferreira et al. (2013), where the authors surveyed 29 different BCI applications. It was concluded that BCI causes a high level

Table 4 Hybrid BCI games

Paper	Electrodes	N
Mühl et al. (2010)	NA	2
Pires et al. (2011)	12	NA

Fig. 7 Types of hybrid BCI (Banville and Falk 2016)



of fatigue and demands high concentration or attention to stimulus, that it has a very low information transfer rate, and that the research community is primarily concerned with proofs of concept rather than innovative and functional design. Current difficulties encountered by contemporary BCI research are also pointed out in Lotte (2011). As the authors noted, the research community continues to work on proofs of concept with regards to control modalities. The experimental environment is far from being established and uniform, without noisy distractions. Therefore, the real-world performance of these prototypes, regardless of the reported efficacy, will be significantly lower than reported. Authors pointed out the unexplored opportunities reflected in combining established control modalities, such as keyboard and mouse, with BCI, and also stress the possibilities of harnessing the user state monitoring capabilities of BCIs to augment the gaming experience. Apart from numerous uses of BCI in games, health care, and serious games, there is an obvious lack of commercially successful BCI games for healthy users. For this to happen, there needs to be viable commercially available BCI device, along with attractive applications or games. The feasibility of using off-the-shelf hardware by researchers in research was examined in Vourvopoulos et al. (2016), where three BCI devices have been assessed, and authors concluded that regardless of the BCI paradigm medical grade systems do not necessarily add value on the experience level of the users, and that the performance of non-expert users can be accomplished without high-end devices. Apart from hardware issues, the methodology of conducting training and calibration sessions needs to be changed as well. Issues with the traditional MI training protocol were elaborated in Jeunet et al. (2016). Here, the MI-BCI training procedure was used for non-BCI motor tasks. In total, 17% of participants ($N = 54$) did not succeed in the subsequent task. This number is close to the BCI illiteracy rate (Vidaurre and Blankertz 2010). This finding suggests that the sub-optimal training protocol might greatly contribute to the BCI illiteracy phenomena. Current studies are experimenting with replacement of the Graz protocol with games, immersive VR, adding factors such as competitiveness, multimodal feedback, and input, effectively creating more motivating environment. Although, as we discussed before, not every person is capable of performing adequately in SSVEP or P300 BCI, the performance across subjects with these modalities is less subject to the various factors inhibiting performance in a MI-BCI (Ahn and Jun 2015). However, there are some efforts to predict low performing individuals (Ahn et al. 2013; Blankertz et al. 2009, 2010) and to implement a screening protocol in order to provide tailored interaction schemes.

In the case of ERP modality, the potential sensory impact a stimuli has can be easily assessed and prototyped in a gaming context, and adhering to the canonical schemes of evoking a specific potential is quite restrictive. Instead, the developers of BCI games should consider leveraging all the flexibility of the rich graphical environment in order to seamlessly integrate the triggering stimuli in a non-distracting way.

BCIs attract researchers with diverse backgrounds, and the research community has different expectations, visions, and understanding of the implications these interfaces carry. This is evident in the variety of proposed BCI taxonomies. It is obvious that there is significant overlap in these definitions, which shows the lack of coordinated efforts in BCI research. Opinions of numerous researchers on important issues concerning BCI were assessed during the 4th International BCI Meeting at the Asilomar conference. Here a poll was conducted among the attendees that comprised of researchers and stakeholders of the future of BCI (Nijboer et al. 2013). The questionnaire results that summarize opinions of 144 participants highlight that there is little consensus on what BCI actually represents. A majority (65.7%) view passive interfaces as BCIs, while only 9% of the respondents believe a BCI is only a BCI when it is used solely for the purpose of sending a message or command. Nevertheless, 79% of the respondents agreed that a standard BCI definition should be clarified within 5 years. Another opinion poll (Ahn et al. 2014) examined opinions of researchers, game developers and users around the world (294 participants) showed that by far Prosthesis and rehabilitation are regarded as the most promising field of application, followed by the games. With regard to the control paradigm, the users and developers preferred active and reactive BCIs, while the researchers were inclined to mention reactive BCI as the most appropriate. The majority of the demographic considered the affordable price for a commercial BCI gaming peripheral should be around 100 USD. As a key to BCI gaming success, the developers emphasized the importance of a suitable development platform, while the researchers expressed the opinion that simple and precise devices along with positive public awareness of BCIs are high priorities. Although the acceptable price range is clear, the proper performance benchmarks need to be established. Challenges of BCIs lie not only in meeting real-world expectations, but also in ethical and legal implications, which will be of increasing concern as the interface matures.

6 Conclusion

Gaming implementations of BCIs tackle the biggest challenges of the BCI of today. For an interface to be effective, the interaction must be seamless, and user experience must be of prime concern. Since all the BCI paradigms depend on user motivation and mood, games are a natural research tool to probe possible avenues of development. In spite of the fact that BCI research of today is far from applications for healthy persons, the games offer a research platform that has been able to produce interesting breakthroughs in EEG BCI. On the other hand, lack of better performing, low cost devices are a persistent problem, and future progress in this niche will depend on the technical advances further ahead. On the other hand, the availability, reliability, and performance of emerging off-the-shelf BCI devices are increasing. However, we can see that the use of consumer devices is almost exclusively in the field of NF and affective interfaces, which would indicate lower performance requirements of such systems for given uses. In NF and affective BCI research that was brought to consideration in this paper, 20 out of 29 papers used a consumer-grade system. ERP/EP implementations on the other hand used consumer EEG devices in only 4 out of 23 publications, while MI modality has not been implemented using a consumer system at all. Although there has been significant research conducted in EEG-based BCIs and games, there is still a lack of full-feature games or wider use of commercial BCIs applications in general (apart for clinical applications and other narrow-niche NF applications). Freely available off-the-shelf EEG devices however did not manage to trigger widespread adoption of EEG BCI nor a measurable impact on the gaming industry. Moreover, considering that there have not been significant attempts at hybrid BCI games, we can conclude that research in this area is severely neglected. If BCIs are to succeed as a viable interface in everyday life, the research community needs to explore ways of leveraging benefits of multiple interaction paradigms along with multimodal approaches in order to mitigate serious performance challenges. Nevertheless, there is significant progress in the efforts to seamlessly embed the calibration and training phase, while with stimuli-dependent modalities, the tendency is to blend in the triggering stimuli in the game environment (in the case of ERPs). Finally, advances in sensor technology have lead to a reduction in the number of required electrodes and increasing use of dry electrodes. Such progress shows that EEG-based interface is still the most likely candidate for the BCI of the future.

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