Neurophysiological methods for monitoring brain activity in serious games and virtual environments: a review

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Abstract: The use of serious games and virtual environments for learning is increasing worldwide. These technologies have the potential to collect live data from users through game play and can be combined with neuroscientific methods such as EEG, fNIRS and fMRI. The several learning processes triggered by serious games are associated with specific patterns of activation that distributed in time and space over different neural networks. This paper explores the opportunities offered and challenges posed by neuroscientific methods when capturing user feedback and using the data to create greater user adaptivity in game. Existing neuroscientific studies examining cortical correlates of game-based learning do not form a common or homogenous field. In contrast, they often have disparate research questions and are represented through a broad range of study designs and game genres. In this paper, the range of studies and applications of neuroscientific methods in game-based learning are reviewed.

Keywords: neurophysiological methods; brain; serious games; games; virtual environments; virtual reality; NIRS; near infrared spectroscopy; EEG; electroencephalography; fMRI; functional magnetic resonance imaging; neuroscience; learning; game-based learning.

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1 Introduction and background

Serious games are increasingly adopted as novel solutions for supporting educational and training activities (e.g. de Freitas and Maharg, 2011; Zyda, 2005). There are at least two ways in which neuroscientific methods of collection of brain activity can be used to provide information for serious games and virtual environments. First, these methods are useful to assess the efficacy of game-based approaches. As with any other learning technology, the efficacy and value of game-based approaches must be carefully assessed, particularly in terms of their wider role in blended or exploratory pedagogic approaches (e.g. de Freitas and Neumann, 2009). Second, these methods are suitable to enhance game adaptivity to the user by collecting user data dynamically. Neuroscientific methods can be used to collect brain activity and then be used as feedback to the user (Howard-Jones et al., 2011; Ninaus et al., 2013), allowing the game to adapt to the user's interactions and inputs to the user.

This paper considers both of the approaches in relation to a literature review and an assessment of some key studies in the field. This review examines neuroscientific studies on computer games, serious games and virtual environments with regard to learning processes, such as attention, cognitive workload, sense of presence and immersion. An extensive examination of the scientific literature was undertaken. This approach was not restricted to any specific time frame but included all the literature available in databases such as PubMed, ScienceDirect and Scopus. Additionally, other relevant conference proceedings and the expertise of the authors were utilised.

Regarding the assessment of the efficacy of game-based approaches, action video games have been shown to enhance a wide variety of perceptual skills such as visual selective attention (Green and Bavelier, 2003) and spatial attention and mental rotation (Feng et al., 2007). However, some studies report that extensive video game practice does not significantly enhance performance in several cognitive abilities, such as attention, memory and executive control in non-gamers (Boot et al., 2008). Yet, extensive experience with action video games may enhance players' top-down attentional control, which can help them to rapidly distinguish between relevant and irrelevant information (Chisholm et al., 2010). Some researchers assume that video game experience can improve the ability to extract task-relevant information, especially in the domain of visual perception (Green et al., 2010). However, there are many more aspects to consider such as expectations (Bengtsson et al., 2009), the sense of agency (Sharot et al., 2010), personal experience (Sharot et al., 2007), flow (e.g. Berta et al., 2013) and the brain reward system (Clark, 2010). For effective transfer of learning to occur, users need sufficient practice with the serious game and therefore the game has to be sufficiently compelling for users to put in the requisite amount of time and effort (Suilleabhain, 2008).

Regarding the enhancement of game adaptivity, a diverse range of Human–Computer Interaction (HCI) technologies and methods have been employed in serious games. Several studies examined how these novel interfaces, such as haptics and augmented reality, can be effectively integrated with game-based learning (Arnab et al., 2010; Bellotti et al., 2010; Liarokapis et al., 2009; Prensky, 2003). Amongst these HCI studies with games, neuroscientific methods provide a new and relevant approach allowing for identifying the quality of affective feedback from users (e.g. Rebolledo-Mendez et al., 2009). Given the close relationship between cognitive learning processes and neurophysiology this is perhaps unsurprising. However, the issue of how user inputs can be fed back into the game adaptivity is an emerging line of game-related research that not only provide efficacy but also as an adaptive element in HCI and games. Recently, specific brain regions have been identified that indicate brains' preparedness to learn (Yoo et al., 2012). This shows new challenges for learning improvement if a link between brain activity and learning success can be solidly proven in dynamic learning games' studies. One area of use of the research in applied learning situations consists in training how to make the player enter the 'prepared' brain states before learning starts. Another field of investigation is stimulating areas of the brain that are to be involved in the learning process. It has been shown that externally modulating the brain activity can boost its performance in arithmetic (Cohen-Kadosh et al., 2010), problem-solving (Chi and Snyder, 2012), language learning (Flöel et al., 2008) and movement (Reis et al., 2009). Additionally, real-time strategy video games can train executive control functions, such as task switching, working memory, visual short-term memory and reasoning (Basak et al., 2008).

The neuroscientific method most often used in a gaming environment is electroencephalography (EEG). EEG is commonly favoured for its lightweight, non-invasive and unobtrusive nature. However, other neurophysiological methods such as Functional Magnetic Resonance Imaging (fMRI) and Functional Near-Infrared Spectroscopy (fNIRS) are also increasingly popular as a technique to assess and understand learning processes in game environments. In the next section, we outline a range of examples of the use of these techniques, and discuss the various indicators they can provide to the learning process, as well as how this information can be fed back to learners, inform educators or function as a control input for reinforcing feedback.

2 Applications of neuroscientific methods in game-based learning

In this section, applications of neuroscientific methods in game-based learning environments are broadly classified in terms of the underlying technology: EEG, fMRI and fNIRS. For each technology, a range of studies is presented, which has shown relevance for measuring physiological states or transitions, and factors salient to learning processes, such as attention, cognitive workload, sense of presence and immersion (Table 1). Additionally, we will highlight the strengths and weaknesses of these neuroscientific methods. Following this description, the discussion section critically identifies the commonalities in these studies and suggests a number of research areas that we consider as key to be addressed in the future.

Table 1 Neuroscientific studies for monitoring brain activity in serious games and virtual environments

Reference	*Neuroscientific Method*	*Method*	*Purpose*
Allison and Polich (2008)	EEG	Game	Using ERPs to assess cognitive workload during gaming
Pugnetti et al. (1996)	EEG	Virtual Reality	Navigating through an interactive virtual environment; Using ERPs to get insight about participants' engagement level
Kober and Neuper (2012)	EEG	Virtual Reality	Navigating through an interactive virtual environment; Using ERPs to get insight about participants' engagement level
Salminen and Ravaja (2007)	EEG	Game	Gaming events with different cognitive demands were associated with EEG oscillations changes
Kramer (2007)	EEG	Game	EEG oscillations used as predictors of performance in video game
Yamada (1998)	EEG	Game	EEG oscillations to assess attention, concentration, fatigue and interest during gaming
Nacke et al. (2010)	EEG	Games	Modulations in EEG during gaming related to mental effort
Pellouchoud et al. (1999)	EEG	Games	Modulations in EEG during gaming related to mental effort
Salminen and Ravaja (2008)	EEG	Games	Modulations in EEG during gaming related to mental effort
Baumgartner et al. (2006)	EEG	Virtual Reality	Assessing the presence experience in games with EEG
Kober et al. (2012)	EEG	Virtual Reality	Assessing the presence experience in games with EEG
Plotnikov et al. (2012)	EEG	Game	Measuring flow with EEG
Berta et al. (2013)	EEG	Game	Measuring flow with EEG
Kosmadoudi et al. (2010)	EEG	Game-based environment	Stress levels recorded with EEG and galvanic feedback in a game-based environment
Liu et al. (2010)	EEG	Virtual Reality	Using EEG and Galvanic Skin Response to assess emotional status of the user
Finke et al. (2009)	EEG	Game	EEG BCI used for controlling a character on a three-dimensional game board
Nijholt et al. (2009)	EEG	Review	BCI
Scherer et al. (2013)	EEG	Game	Controlling a MMORPG with a BCI
Lin and John (2006)	EEG	Game	Quantifying Mental Relaxation with EEG in a simple computer game
Ninaus et al. (2013)	EEG	Review	Neurofeedback
Rebolledo-Mendez et al. (2009)	EEG	Virtual Reality	EEG to assess attention levels

Table 1 Neuroscientific studies for monitoring brain activity in serious games and virtual environments (continued)

Reference	*Neuroscientific Method*	*Method*	*Purpose*
Hummer et al. (2010)	fMRI	Game	Examining the impact of a violent video game on the brain
Mathiak and Weber (2006)	fMRI	Game	Examining the impact of a violent video game on the brain
Wang et al. (2009)	fMRI	Game	Examining the impact of a violent video game on the brain
Baumgartner et al. (2008)	fMRI	Virtual Reality	Cortical correlates of presence experience
Jäncke et al. (2009)	fMRI	Virtual Reality	Cortical correlates of presence experience
Klasen et al. (2012)	fMRI	Game	Cortical correlates of flow
Goebel et al. (2004)	fMRI	Game	Controlling a computer game based on table tennis
Izzetoglu et al. (2004)	fNIRS	Game	Game difficulty associated with oxygenation levels
Matsuda and Hiraki (2006)	fNIRS	Game	Examining cognitive load of video games
Nagamitsu et al. (2006)	fNIRS	Game	Examining the attention demand or task load from video games
Hattahara et al. (2008)	fNIRS	Game	Identifying differences in changes in blood oxygenation between novice players and master-level players
Girouard et al. (2009)	fNIRS	Game	Blood oxygenation differences were used to distinguish between low and high game difficulty
Tachibana et al. (2011)	fNIRS	Game	Insights into temporal relationships of blood oxygenation during real motor tasks by using a dance video game
Matsuyama et al. (2009)	fNIRS	Game	Controlling a humanoid robot with real-time fNIRS

2.1 EEG

With EEG, electrical activity of the brain can be recorded non-invasively at the scalp surface, which reflects the summed potential of ionic currents across membranes of single cells, thus a direct method of measuring brain activity. Electrodes placed on the scalp pick up the signals mostly from brain regions near the surface of the head (Kropotov, 2009). These signals can be differentiated in two groups: first, the Event-Related Potentials (ERPs), such as P300 evoked potentials. The occurrence of particular events or stimuli can induce changes in the activity of neuronal populations that are generally called ERPs. Generally, averaging procedures are used to identify such ERPs (Pfurtscheller and Lopes, 1999). Second, the event-related change in the ongoing EEG activity in specific frequency bands, such as desynchronisation or synchronisation of alpha and beta rhythms. Owing to the fact that EEG is based on measuring electrical brain activity, it has a very high-temporal resolution and can detect changes of brain activation within milliseconds.

EEG applications in game-based learning: In many EEG studies, neuronal responses to instantaneous game events are recorded. By averaging these events, ERPs can be detected (Pfurtscheller and Lopes, 1999). For instance, ERPs can then be used to assess cognitive workload during gaming. In so-called dual-task paradigms, infrequent game-unrelated stimuli such as tones are presented during playing games. These stimuli can elicit ERPs in the EEG. There is evidence that the amplitude of these ERP varies depending on the cognitive workload induced by playing a game (Allison and Polich, 2008).

General effects of interaction with virtual environments on nervous system activity have already been explored in the 1990s. Pugnetti and colleagues (1996) investigated the correlates of virtual reality experience using EEG. They implemented interactive virtual environments with tasks similar to those of well-established tests of categorisation and cognitive flexibility, e.g. the Wisconsin Card Sorting Test (WCST). For instance, participants had to navigate quickly from one virtual room to the next until the virtual environment exit was reached. Additionally, during the navigation task cortical auditory ERPs were elicited by releasing footstep sounds binaurally as they moved forward in the virtual world. Engaging in the virtual reality task substantially reduced the amplitude of specific ERP components. This result might show that if participants are engaged in virtual environments, only a fraction of their processing abilities is devoted to stimuli such as the footstep sounds, which they did not have to process actively. Hence, the amplitudes of auditory ERP in the EEG elicited by footsteps sounds were reduced.

In a recent study by Kober and Neuper (2012), auditory ERPs elicited through presentation of infrequent tones were used to examine attention allocation between virtual reality (VR) and the real world. ERP amplitudes could differentiate between participants that focused their attention on VR (highly engaged) and participants that were less immersed in VR (less engaged). This study may demonstrate a new and objective way of measuring engagement, respectively, the sense of presence in a virtual environment. Highly engaging virtual environments may support attention and therefore learning. The question on what specific learning content a highly engaging virtual environment is beneficial has not been answered yet.

Besides analysing time-locked ERPs, the EEG can be recorded continuously during a gaming session. The continuous EEG oscillations during gaming may then be compared with the EEG activity during a resting or baseline period before or after playing a game. These EEG oscillations can shed light on cognitive and emotional processes underlying the gaming process (Niedermeyer and Lopes da Silva, 2005). For example, oscillatory brain responses evoked by video game events were examined by Salminen and Ravaja (2007). They found that gaming events with different cognitive demands were associated with different changes in EEG oscillations. There is also evidence that EEG oscillations can be used as predictors of performance in video games (Kramer, 2007). Furthermore, EEG oscillations are useful for assessing attention, concentration, fatigue and interest during playing games (Yamada, 1998). Generally, changes in EEG oscillations during gaming were examined in the context of different research questions, such as oscillatory activation induced by violent video games, mental effort-related EEG modulation during gaming and affective game–play interaction (Nacke et al., 2010; Pellouchoud et al., 1999; Salminen and Ravaja, 2008).

Using EEG recordings, Baumgartner and colleagues (2006) found a positive relationship between presence experiences (sense of being there, Slater, 2003) in virtual worlds and cortical activation in parietal brain areas known to be involved in spatial navigation. The subjects' task was to passively watch different immersive virtual roller coaster scenarios during the EEG measurement and to rate their feeling of presence. Users experiencing a higher level of presence showed an increased event-Related Desynchronisation (ERD) in the alpha band (8–13 Hz) reflecting increased activation (Pfurtscheller, 1989) in parietal brain regions. Kober et al. (2012) replicate these findings in an interactive virtual environment, where subjects navigated freely through a virtual world. Baumgartner and colleagues (2006) and Kober et al. (2012) concluded that parietal brain areas might play an important role in the presence experience because these areas are involved in generating an egocentric (body-centred) representation of space (Maguire et al., 1998; Maguire et al., 1999). Because the presence experience is among other definitions also defined as egocentric spatial experience of virtual worlds, it might be that an egocentric view provided by the parietal lobe is essential for the spatial presence experience in virtual environments (Baumgartner et al., 2008; Jäncke et al., 2009; Kober et al., 2012).

A further interesting empirical study, where neurophysiological methods have been used to examine game-related subjective experiences, was conducted by Plotnikov and colleagues (2012; see also Berta et al., 2013). The researchers reported initial data on the monitoring of the player flow status with a commercial four electrode EEGs. The study examined if it is possible to statistically distinguish a flow from a boredom condition. The results – even if limited because of the small sample size of the test – are promising and enable further research.

EEG has also been used to investigate the stress level in order to find out how the design of the user interface could affect an engineers' productivity (Kosmadoudi et al., 2010). The research questioned whether a game-based environment for engineering product design could bring about any positive benefits. The pilot study indicated that as design tasks transit from precise engineered shapes to freeform, performance and stress levels recorded with EEG frequencies and galvanic feedback in a game-based design environment were significantly lower. The exercise was meant to distinguish the difference in cognitive load and interface appreciation between that of a highly structured virtual design environment and that of a lesser constraint one. The basis was on tasks rather than distinct events.

Besides using EEG for assessing and monitoring cognitive processes, EEG can also be used to provide feedback and hence make games adaptive. Continuous EEG recording with or without the combination of autonomic variables (heart rate, respiration rate) can also be used to control adaptive environments. A time-power analysis on continuous EEG and Galvanic Skin Response (GSR) reported the emotional status of the user on an engineering design task in a computer-aided design environment (Liu et al., 2010). It revealed a non-obstructed means of evaluating the affective effects of the user interface design in a virtual environment, as well as providing the environment with the ability of adaptive automation with the human factor.

Another application field is Brain–Computer Interface (BCI). BCIs can provide people with a new non-muscular channel for controlling games (Finke et al., 2009; Nijholt et al., 2009; Scherer et al., 2013). BCI can be used as an extra modality added to game designs, so that gamers can consciously try to interact within the game environment. Another practical implementation of BCI in serious games could be passive

BCIs (Venthur et al., 2010; Zander and Kothe, 2011) as well as neurofeedback (Lin and John, 2006; Strehl et al., 2006; for a review, see Ninaus et al., 2013). In neurofeedback applications users can learn to control their own global brain activity to get into a state of mind more suitable for learning and so optimising learning success. In a study of Rebolledo-Mendez and colleagues (2009), a commercial BCI was tested for usability in a virtual environment using computer science learning tasks. Results showed a correlation between self-reported and actual attention levels measured by the device. Further studies are needed to examine the benefits and reliability of commercial BCIs measuring attention levels in serious games and virtual environments.

These feedback and BCI devices can be used with serious games as a source of feedback from the learner and as an interface device within the game environment, but more studies need to be undertaken to ensure that the feedback is accurate and supports positive learning transfer.

Currently there is a shift from traditional individual learning to collaborative learning environments. Collaboration presents 'coordinated effort to solve a problem together' (Roschelle and Teasley, 1995). People often have different skills and experiences. By collaborative problem solving they learn in the first place to integrate and coordinate their collective knowledge. Dumas and colleagues (2010) conducted a study in which two persons in separate rooms were instructed to make meaningless gestures with their hands. Participants were filmed and they could see their partners' hands through the TV screen. The experiments showed that the states of interactional synchrony (similar gestures) correlated with emergence of an interbrain synchronising network. This is in line with the notion of 'awareness' (Dourish and Bellotti, 1992) that promotes 'an understanding of the activities of others, which provides a context for your own activity' (Dumas and colleagues, 2010; Dourish and Bellotti, 1992; Halimi et al., 2011). Studies exploring the mirror neuron system – which is engaged while imitating or simulating the actions of others and might be the basis for social processes, such as imitation, empathy, action understanding and perspective taking (Rizzolatti and Craighero, 2004) – have shown different EEG activation in conditions in which participants performed synchronised finger movements together with their partner or performed finger movements on their own independently (Naeem et al., 2012). Furthermore, activation of the mirror neuron system could be an indicator if a game character or robot is still 'human' enough to engage the mirror neuron system (Obermann et al., 2007).

2.2 *fMRI*

fMRI is a popular non-invasive neuroscientific method. Magnetic resonance imaging uses strong magnetic fields to create images of biological tissue. fMRI allows to measure participant's Blood Oxygenation Level Dependent (BOLD) response with an excellent degree of spatial resolution to give information on task-specific activation in a variety of brain regions (Detre and Wang, 2002). The BOLD reflects relative changes in the concentration of deoxygenated haemoglobin evoked by sensory, motor and cognitive processes. The concentration of deoxygenated haemoglobin increases rapidly and peaking at about 6 s after stimulus onset, before declining to a minimum value about 12 s after onset and returning to baseline about ten seconds after stimulus onset (Huettel et al., 2009). Therefore fMRI can provide, among other things, relevant information about the neuroanatomical localisation of regions responsible for learning and interacting in serious games and virtual environments. The information gained from fMRI can be used, for example, to improve the effectiveness of serious games or how games affect the player's brain.

fMRI applications in game-based learning: For instance, fMRI has been used to investigate how playing a violent video game impacts the player's brain. Violent scenes in the video games revealed significant modulations of BOLD response in frontal brain regions when comparing participants who played violent video games and those who did not (Hummer et al., 2010; Mathiak and Weber, 2006; Wang et al., 2009). Video games of different genre that require diverse cognitive resources lead to differences in the BOLD response (Saito et al., 2007). Hence, fMRI turned out to be a valuable tool for examining cortical correlates of the gaming process as well. An fMRI study using virtual roller coaster scenarios found that the presence experience in simulating environments is linked to activation of a distributed network in the brain, e.g. activation in the dorsal and ventral visual stream, the parietal cortex, the premotor cortex, mesial temporal areas, the brainstem, the thalamus and the dorsolateral prefrontal cortex (DLPFC) (Baumgartner et al., 2008; Jäncke et al., 2009). Jäncke and colleagues (2009) supposed that the DLPFC could be a key node of this network because it modulates or down-regulates the activation of the network and consequently regulates the associated experience of presence.

Another very important construct for investigating serious games and virtual environments is 'flow'. Klasen and colleagues (2012) showed that even such a subjective feeling is to some extent measureable with neurophysiological methods. These authors acquired fMRI data during free play of a video game and analysed brain activity based on the game content. They developed a content coding system which allowed for a reliable and objective description of in game events and the actions of the player. The detailed content analysis of the players' game sessions allowed the authors to analyse the fMRI data with respect to specific factors of the subjective game experience 'flow'. Klasen and colleagues (2012) found that flow is characterised by specific neural activation patterns in reward-related midbrain structures, as well as cognitive and sensorimotor networks. Klasen and colleagues (2012) argued that the activation in sensory and motor networks could underpin the central role of simulation for flow experience. They assume that this sensorimotor activation reflects the simulation of physical activity in the game.

Numerous cognitive properties cannot be described through single brain areas, as shown by Klasen and colleagues (2012) for 'flow'. The majority of cognitive processes rely on a wide-spread network in the brain. For instance, creative thinking is considered as a complex mental ability domain (Fink et al., 2009) and one of the most extraordinary capacities in humans (Dietrich and Kanso, 2010). Therefore, the exploration of neurophysiological correlates of creativity could contribute to better tune and focus specific educational actions oriented to creativity enhancement in the context of serious games. Following the examination of 72 studies including fMRI as well as EEG, Dietrich and Kanso (2010, p.822) came to the conclusion that "creative thinking does not appear to critically depend on any single mental process or brain region, and it is not especially associated with right brains, defocused attention, low arousal, or alpha synchronisation". Haier and Jung (2008, p.171) observed that integrating neuroscience findings into education practices is "a daunting challenge that will require educators to re-examine old ideas and acquire fundamental backgrounds in new areas". This implies, for instance, extending and empowering group work and collaborative learning activities, taking into account that neuroscience findings have already proven that accessing the ideas of others may enhance creativity by reducing the need to deactivate automatic bottom-up processes, associated with fixation on own ideas (Fink et al., 2010).

The different aspects of collaboration and social interaction, such as joint attention or decision-making, also have been investigated in several psychophysiological studies using fMRI too. Williams and colleagues (2005) identified a number of clusters of additional activity in the joint attention settings in comparison to non-joint attention conditions. Furthermore, Martena et al. (2008) also discovered additional activation patterns in the Posterior Superior Temporal Sulcus (pSTS) region in case of joint attention. In both studies, participants had to move their eyes. In joint condition, participants should shift their gaze towards the target guided by a gaze of a face, which was presented on the screen in front of them.

Not only learning with more people but also with more modalities might have an advantage. Shams and Seitz (2008) advocated multisensory teaching approaches as mirroring more closely evolved learning processes, suggesting unisensory approaches are sub-optimal and that their selection is based in practicality rather than pedagogy. For instance, visual and auditory information are integrated in performing many tasks that involve localising and tracking moving objects. Based on their reviews, they assume that the human brain has evolved to learn and operate optimally in multisensory environments (see also Kalyuga et al., 2004, which showed that redundant information presented in different modalities can actually interfere with learning). Recently, multisensory modulations and activations have been discovered in early stage perceptual processing brain areas, which have long been claimed as ‘sensory specific’ (Shams and Seitz, 2008). Shams and Seitz (2009) suggest that training protocols that employ unisensory stimulus environments do not engage multisensory learning mechanisms and, therefore, might be sub-optimal for learning. Thus, multisensory stimulus environments are more effective for learning, because they can better resemble natural settings. This finding seems to correlate with other studies in serious games research where immediate feedback to learners and multisensory environments are more effective than traditional learning approaches (Knight et al., 2010). The main lesson for serious game design here is that feedback to the learner needs to be formative in games and that multisensory environment can be more effective as a design strategy for effective learning with games.

Another application field where fMRI can provide feedback is real-time fMRI (Weiskopf, 2012). However, due to the fact that real-time fMRI is a relatively new feedback method, only a few real-time fMRI studies implemented gaming elements as feedback modality so far. For instance, self-regulated brain activity has been used to play a computer game based on table tennis inside the MRI-scanner (Goebel et al., 2004).

2.3 fNIRS

Functional Near-Infrared Spectroscopy is a non-invasive optical neuroimaging technique discovered in 1992. fNIRS can be used to explore the functional activation of the human cerebral cortex. This neurophysiological method uses the oxygenation and haemodynamic changes in the blood of the human brain (Ferrari and Quaresima, 2012). fNIRS is based on the same metabolic signal as the fMRI, the BOLD response. More precisely, fNIRS takes advantage of the different absorption spectra for near infrared light of oxygenated and deoxygenated haemoglobin and allows to measure relative changes in haemoglobin concentration (Villringer and Chance, 1997). fNIRS relies on the principle of neurovascular coupling that is local neural activity leads to a vascular response in the active brain area that causes an inflow of oxygenated blood. As a result, deoxygenated haemoglobin decreases, whereas oxygenated haemoglobin increases in the active brain region. This circumstance is the major source of the BOLD contrast as measured with fMRI (Huettel et al., 2009; Telkemeyer et al., 2011). However, fNIRS allows for the recording of changes in the BOLD response with a much higher temporal resolution than fMRI but at the costs of lower spatial resolution and no sensitivity to haemodynamic activity in deep brain regions.

fNIRS applications in game-based learning: Many game studies used fNIRS to examine haemodynamic changes in frontal brain areas during playing video games. The majority found a decrease in oxygenated haemoglobin during gaming which might result from attention demand or task load from the video games (Izzetoglu et al., 2004; Matsuda and Hiraki, 2006; Nagamitsu et al., 2006). Additionally, fNIRS measurements were used to examine differences in blood oxygenation between novice players and master-level players (Hattahara et al., 2008). These identifiable measures between experienced and novice players have particular appeal, as they allow for the development of baselines against which future learners can be assessed.

fNIRS is also used to investigate cognitive load. Prefrontal cortex plays an important role in many higher cognitive functions and video game play leads to a reduction in oxygenated haemoglobin which rapidly recovers after the end of a game (Matsuda and Hiraki, 2006). Girouard and colleagues (2009) used fNIRS to measure the response to both low and high game difficulty and found a significant difference between the pooled group means. However, the small effect size meant that a classifier algorithm had difficulty distinguish changes within individuals. A military simulator (Warship commander) was used to vary task difficulty while fNIRS was used to measure changes in dorsolateral prefrontal cortex oxygenation levels (Izzetoglu et al., 2004). An inverted U-type relationship where oxygenation levels increased with increasing task difficulty until it became too difficult and then they started to decline was observed. Some of the authors of this paper have undertaken small pilot studies to determine whether fNIRS can be used as a valid measure of effective learning, and these studies are ongoing, using simple and more complex serious games.

Besides using fNIRS for monitoring cognitive processes, fNRIS can also be used to provide real-time feedback. However, game elements have hardly been implemented in real-time fNIRS studies so far. In one of these studies, real-time fNIRS was used to control a humanoid robot. Participants performed different mental tasks to generate motion in the robot (Matsuyama et al., 2009). It is conceivable that real-time fNRIS could also be used to control games or in game characters.

2.4 Pros and cons of different neurophysiological methods

Different neurophysiological methods can be used for monitoring and assessing cognitive processes in serious games and virtual environments. However, the different methods are associated with various advantages and disadvantages. Depending on the research question, study design, and hypotheses one neurophysiological method is more suitable than the other. For instance, EEG has a high-temporal resolution (<1 ms) compared with fNIRS and fMRI (> 1 s). Thus, using EEG to add a further possibility to interact with the game or to control the game itself, respectively, is recommendable since the electrical activity of the brain can be detected immediately and feedback to the user with no time delay. fNIRS and fMRI, which are based on relatively slow metabolic changes, would result in a delayed feedback and the interaction with the game would not feel responsive to the user.

However, if someone is interested in examining cognitive processes and its neural substrates during gaming, especially in deep brain structures such as the amygdala or hippocampus, fMRI is a superior method. fMRI has a high-spatial resolution compared with EEG and fNIRS, and enables the researcher to make assumptions about the involvement of different brain areas and its relevance for gaming. EEG allows only limited access to deep brain structures, depending on the number of electrodes used. fNIRS enables us to measure changes in haemodynamic responses only at the surface of the brain (Huppert et al., 2006).

In neuroscientific studies the quality of the assessed neurophysiological data is crucial. Compared with EEG and fMRI, fNIRS has the advantage of a reduced sensitivity to motion-artefacts and therefore allows a higher degree of movement (Lloyd-Fox et al. 2010; Nambu et al., 2009). Tachibana and colleagues (2011) demonstrated that fNIRS can be adequately used to measure brain activation when playing a dance video game, where participants had to move extensively. While lying inside the MRI-scanner, participants should not move their head to avoid motion artefacts which can affect the quality of the fMRI data enormously.

A further important issue is the comfort for participants during measurements, especially when examining subjective experiences during gaming such as flow. Distractions due to the neurophysiological measurements could decrease or hamper such game experiences. For instance, some participants experience discomfort inside an MRI-scanner because of the noise and the narrow scanner. The montage of EEG electrodes is with some EEG systems very time-consuming and repeated measures might be uncomfortable since there is abrasive gel needed, which could lead to skin irritations. In contrast, the preparation time for fNIRS is quite fast. Compared with fMRI, which is locally bounded to the installation site, fNIRS and EEG are more flexible and portable systems. Recently, easy-to-use and wireless devices are available which might be useful when using fNIRS or EEG in the gaming context (Muehlemann et al., 2008; Ninaus et al., 2013; Sitaram et al., 2009).

Finally, it should be noted that the costs of the different neurophysiological methods are quite different. While fMRI is the most expensive method in terms of maintenance and purchase, EEG is highly cost-effective.

In summary, for the assessment of the efficacy of game-based approaches, all three discussed neuroscientific methods are more or less suitable. If examining brain responses to fast events of a game, the EEG with its high-temporal resolution should be the method of choice. In contrast, for the investigation of neuronal responses during gaming in deep brain structures, fMRI with its high-spatial resolution is the best choice. But if the comfort for the gamer should be maximal, fNIRS is recommended. In the context of using neuroscientific methods to enhance game adaptivity to the user, again the high-temporal resolution of EEG is the most advantageous, since there is no time delay when the electrical activity of the brain is fed back to the gamer in real time during interacting with a game.

3 Discussion

One of the issues emerging from our review and ongoing pilot studies is that there is a lack of a common methodological approach in the use and validity assessment of neuroscientific methods in serious games or games in general. A primary consequence of this is a large number of studies reaching conclusions that might easily be misinterpreted. For example, Derbali and Frasson (2010) deployed a serious game which educated about the problem of world hunger. Whilst playing, the relationship between players' motivation and EEG oscillations was examined. During gaming the players' motivation, measured via survey, was shown to correlate with changes in EEG measurements. Therefore, EEG is suggested to be a valid and objective index of players' motivation during gaming. Yet this makes a significant assumption in suggesting surveyed metrics of motivation which are a true proxy for the latent psychological construct – in fact how motivation is constructed, defined and influences behaviour is far from being universally defined or agreed, which can be solved only with more specific measures of stress and motivation according to established theories and the replication of studies.

This applies equally to commercially available lightweight EEG devices, which often suggest such metrics (e.g. 'attention' and 'motivation'), without providing clarity in their derivation and definition. Furthermore, the placement of the electrodes of such devices is often in a way that records muscle rather than brain activity. This is not to dispute that EEG readings can be correlated to a wide range of learning activities; rather, we argue that attempting to explain the EEG values in terms of emotions and psychological constructs is a step that can rapidly complicate the interpretation, applicability and reusability of findings. Furthermore it is important to decide what neurophysiological method will suit best to the planned research question and experimental design. For example, using fMRI can provide detailed spatial information about specific brain areas and their function, but the temporal resolution is poor, compared with EEG. However, for all neurophysiological measurements, artefacts are a problem, for some more (fMRI, EEG) for some less (NIRS). Nevertheless, the movement always has to be restricted and measurements are usually in the lab in artificial environments. This is a disadvantage for games and virtual realities in which most engagement of the user is desirable and has to be considered very carefully in study design.

Many decisions need to be taken before conducting neurophysiological measurements; therefore, it is essential to have a clear experimental design and hypotheses for psychophysiological studies. For examining basic neurophysiological correlates, the used games should not be too complex. Especially for explorative studies, a simple game design with only few variables should be used to be able to clearly identify which brain processes are involved or which skills are needed during gaming. Using psychophysiological methods in game research has some apparent limitations, as discussed in the previous sections. Nevertheless, if it is used appropriately it is a powerful tool to answer various research questions related to game experience and specific states in the context of learning.

We thus argue that effective study design for serious games should avoid such dilemmas by focusing specifically on direct task performance as a correlate of device measurement. Effectively, this aims at preventing the requisite of a deeper understanding of the neurophysiological processes and psychological constructs affecting performance, while focuses on direct correlates between narrow metrics of task performance and measured readings. Serious games can form a particularly effective basis for this, as game design lends itself easily to the definition and assessment of simple cognitive tasks, as well as their deployment in an experimental context, with a wide range of user performance data collection. Study designs under such a paradigm should focus on defining and understanding expertise at a task established through an understanding of the prior knowledge or measured performance of subjects. These metrics can then be more readily correlated to measurements from EEG, fNIRS, fMRI or other biosensor devices whilst avoiding the pitfalls of attempting to reach broad conclusions regarding the nature and physiology of learning.

Another approach to obtain an effective experimental design is to apply the logic of the additive factor method of Sternberg (1969). The additive factor method was originally used for reaction time measurement to study different stages of information processing. Some of the theoretical assumptions of this method are also used in neurophysiological research. Neuroscientific experiments try to examine specific cognitive properties. By theory-based analysing the subjects' task with psychometric methods, it is possible to identify what cognitive processes or factors are involved in one specific task. Determining every cognitive process in one task is not trivial and is even harder for game environments, due to the complexity of some environments. However, with the knowledge of every cognitive process in one task it is much easier to find or design another task that includes all these processes except the one cognitive process you are interested in. By comparing these two tasks you are able to extract this specific cognitive process from your neurophysiological data.

With respect to study design, comparison of subject matter expert to novice provides a demonstrated means to establish baselines which avoid the difficulty of analysing the complexity of the underlying learning process. Generalisability of such baselines suffers from a close relationship between task and game design, and measured outputs. However, the overlying methodology, which applies baselines developed through a control study of experts against novices, can offer an immediate model for assessment of learners irrespective of task or device. This has the proviso that clear differences can be observed, and the studies we have presented suggest some outcomes which may inform this: for EEG, a common assertion is that measurements can be related to attention and focus. fMRI and fNIRS, by comparison, may offer more specific insight into performance in narrowly defined cognitive tasks.

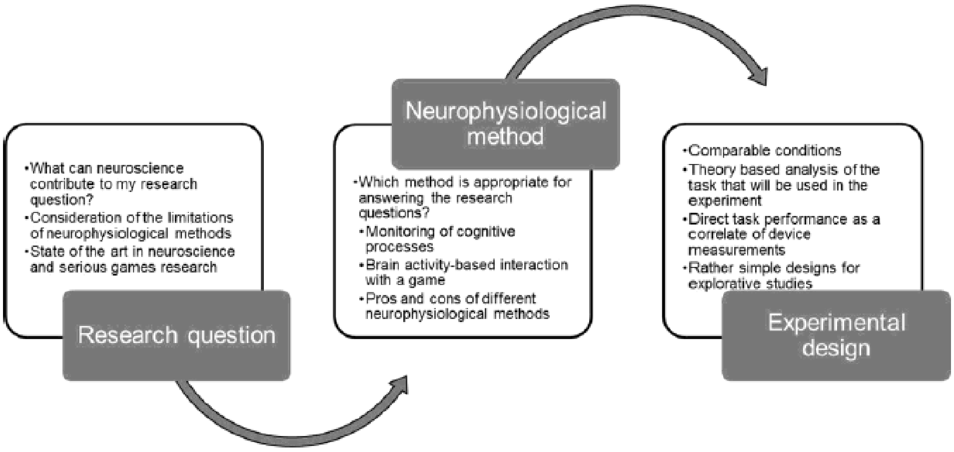
Generalising these assertions, however, is challenging, given the task-specificity of many studies, and the complexity of the underlying physiological system. Therefore, we recommend that baselines should be established on a peer-activity basis. Another challenge is the high inter- and intra-individual differences in neurophysiological measurements. Brain activity might not only be different between participants but also change within one participant conducting exactly the same task more often due to plastic processes of neural activation as a consequence of learning.

A particular challenge to neurophysiological measurements is confirming their measured outputs provide true proxies for learning efficacy. High levels of what might be described as attention – for example, alpha wave activity within a given threshold – do not necessarily correlate with attention towards the desired-learning material. In game environments that use a wide range of stimuli, such as rapid images, auditory content, and significant physical engagement with the interface, many behaviours and actions contribute to measurements, and can easily overwhelm attempts to isolate or consider specific learning processes. Because of these influences it is sometimes very difficult or even impossible to unequivocally interpret the results of neurophysiological measurements that have been recorded during acting in a game environment. Therefore, it is tremendously important to have a well-elaborated study design using conditions that are comparable with each other or are organised according to a factorial schema. This implies to use control conditions that are closest to the stimulus or task condition as baseline. This modus operandi is very important for neurophysiological research and especially important for fMRI studies (Brandt, 2006).

Presence also plays a key role in how users respond and act within a virtual environment (VE). An increased presence experience in a VE should foster the transfer of knowledge acquired in the virtual environment to corresponding real-world behaviour (Slater et al., 1996). This assumption is very important for serious games which base learning around interactions within a VE. Therefore, it seems advisable to use VEs which can increase the sense of being there (presence) for game-based learning. However, presence experience is difficult to measure, due to the subjective character of this concept.

A recent study by Kober and Neuper (2012) showed that ERPs in EEG can be used as a valuable and objective method for measuring the presence in VEs. The highlighted studies in this review demonstrate that the huge potential neurophysiological measurements have for the research of serious games and virtual environments (e.g. measuring subjective experiences in VEs and serious game; Klasen et al. 2012; Kober and Neuper, 2012; using neurophysiological signals as an extra modality for game design; Lin and John, 2006; Scherer et al., 2011).

Figure 1 Visualisation of the planning process of an experiment and summing up relevant points from the discussion



4 Summary and conclusions

The paper summarises some of the leading scientific research studies in the emerging field of neuroscience applied to gaming, where EEG, fMRI and fNIRS are used to investigate the learner's brain activity during game play. The findings indicate that there is a need to focus study designs in a particular way (see also Figure 1), as addressed in the discussion, to ensure that these are effective, focused on direct task performance and thereby narrowing the variables.

The review indicates that there are key benefits in using these neuroscientific techniques for developing serious games, particularly to provide better user feedback and allow designers to get a better understanding of the neurophysiological outcomes of the learner during learning periods and tasks.

The review presented in this paper has scoped the extent of the literature around using EEG, fNIRS and fMRI within game environments for supporting feedback but also for allowing us to trace the impact of game activities within brain activity. Our ambition is to extend the scope of how neurofeedback is currently used in games, as real-time data that can be used to support scaffolded learning and also to allow us to understand more about how game play supports effective learning.

Future work will therefore focus upon user studies where simple and complex learning activities are tested using neurophysiological correlates according to direct task performance with different neurophysiological methods. This approach enables to identify the best applications and uses of these methods for supporting HCI in games environments. The state of the art clearly shows the potential for using these devices. However, we strongly argue that it is hard time to study a rigorous, generalisable method for capturing neuroscientific user data from a player and store it in a real-time executable user model, also extending existing models of feedback (e.g. Dunwell et al., 2011).

Further future research will focus on testing how feedback can be used in real time to make the learner experience more coherent and immersive, as well as recording levels of presence and engagement. Our future work will therefore aim to provide a scientific basis for utilising neurophysiological interaction with learners during learning activities and tasks in game environments and also aim to develop a common methodological approach. Ecological validity, interest and motivators may come at costs of straightforwardness in interpretation of neurophysiological data. Yet, there are ways to reach a balance between both things.

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