Comparing interaction techniques for serious games through brain–computer interfaces: A user perception evaluation study

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A B S T R A C T

This paper examines the application of commercial and non-invasive electroencephalography (EEG)-based brain–computer (BCIs) interfaces with serious games. Two different EEG-based BCI devices were used to fully control the same serious game. The first device (NeuroSky MindSet) uses only a single dry electrode and requires no calibration. The second device (Emotiv EPOC) uses 14 wet sensors requiring additional training of a classifier. User testing was performed on both devices with sixty-two participants measuring the player experience as well as key aspects of serious games, primarily learnability, satisfaction, performance and effort. Recorded feedback indicates that the current state of BCIs can be used in the future as alternative game interfaces after familiarisation and in some cases calibration. Comparative analysis showed significant differences between the two devices. The first device provides more satisfaction to the players whereas the second device is more effective in terms of adaptation and interaction with the serious game.

1. Introduction

The past decade has seen a huge proliferation of commercial interaction devices for video games. Each of these new devices offers a diverse way of interacting with games and computer generated simulations. Typical technologies that these devices use include: optical, auditory, magnetic and inertia sensors. Some can operate as autonomous controllers while others work in hybrid mode (with standard I/O devices such as mouse and keyboard). However, only the hybrid approaches appear to be functional, the rest require a lot of physical effort. This restricts users’ expressive capabilities as well as the information transferred from the user to the computer [1]. Nowadays, non-invasive brain–computer interfaces (BCIs) are getting a lot of attention as alternative human–computer interaction devices for games and virtual environments [2,3].

Non-invasive BCIs operate by recording the brain activity from the scalp with Electroencephalography (EEG) sensors attached to the head on an electrode cap or headset without being surgically implanted. However, they still have a number of problems and they cannot function as accurately as other natural user interfaces (NUIs) and traditional input devices such as the standard keyboard and mouse [4]. The Information Transfer Rate (ITR) of this kind of BCIs is still around 25 bits per minute [5], which makes them much slower compared to traditional input devices such as keyboard (which have typical speed of over 300 characters per minute, roughly 400 bits per minute) [6]. The main reasons behind this are due to bad classification, long training procedures, latency issues and cumbersome hardware [7]. Also, because of lack of training and accessibility in using BCI devices, some people find it difficult to use at all [8].

The majority of BCI studies are performed in laboratory environments under controlled conditions. However this is not always possible in real-life applications and makes current BCI technology not quite suitable for practical applications and widespread use [9]. Game designers and researchers must make sure that BCIs used for gaming environments should not become a barrier in terms of the interaction [10] but on the contrary a more effective medium. Although non-invasive BCI technologies seem to have the potential of providing an environment where “thoughts are not constrained
by what is physically possible" [7], they are still not ready for commercial use.

The main aim of the paper is to examine the effectiveness of two different BCI devices for fully controlling an avatar inside a serious game. The objectives of the paper are threefold. Firstly, to enable a user to fully control an avatar in real-time using only EEG data. Secondly, to qualitatively examine the behaviour and different reactions of the users while playing the game and, thirdly, to test each device in terms of: learnability of the interface using the game, satisfaction of the player, performance of the interfaces and effort expended by the player. Two different EEG-based BCI devices were used; one which requires no calibration (NeuroSky MindSet) and another one that requires the training of the classifiers (Emotiv EPOC). The user is visually stimulated by fully controlling an avatar in the serious game (see Section 3). Two different types of EEG-based BCIs were used: the NeuroSky MindSet and the Emotiv EPOC. All tests (N = 62) were conducted using the same serious game, which was integrated with the devices; participants were divided equally across the devices.

The rest of the paper is structured as follows. Section 2 provides background information for serious games and BCIs. Section 3, presents the serious game that was used as a case study called Roma Nova. Section 4 demonstrates how the two different BCI devices were used for controlling the same serious game. Finally, Section 5 presents the evaluation results and Section 6 the conclusions and future work.

2. Background

Early non-invasive BCI research methods for serious games interaction were usually oriented towards the medical domain rather than entertainment. This kind of research was targeting locked-in patients where haptic and linguistic interfaces fail. The first BCI game was created in 1977. In this game, the user could move in four directions in a maze by fixating on one of four diamond-shaped points periodically flashed. The methodology used was far ahead of its time using online artefact rejection and adaptive classification. The information transfer rate (ITR) was remarkable even for today’s standards being above 170 bits/min [11].

Two survey papers regarding BCI systems have been recently published [12,13]. In another recent paper the opportunities and challenges posed by neuroscientific methods when capturing user feedback and using the data to create greater user adaptivity in games are explored [35]. Berta et al. [36] provides an electroencephalogram and physiological signal analysis for assessing flow in games. The paper defines flow in games as a measure of keeping the player fully immersed and engaged in the process of activity within the game. The evaluation of flow involves a 4 electrode EEG, using the low beta frequency bands for discriminating among gaming conditions. Using simple signals from the peripheral nervous system three levels of user states were branded using a Support Vector Machine classifier. The user states where identified using 3 levels of a simple plane battle game identifying states of boredom, flow and anxiety. The paper argues that a personalised system could be implemented in a consumer context allowing for more flowing gameplay in consumer games.

Moreover, there are a number of experimental applications of using BCIs with computer games. Some of these prototypes are very simplistic and just allow the users to select 3D objects in games based on their attention levels [9]. Nowadays, many different techniques are currently used in BCI systems for user interaction and control. Steady State Visual Evoked Potentials (SSVEP) using flashing lights for visual stimulation, the P300 BCI is measuring the brain evoked response after stimulus onset with a positive curve on the EEG after 300 ms and the ERS/ERD which stands for event related synchronisation/desynchronisation through the imaginary limp movement.

An example of BCI-based input devices using motor-control is the μ rhythm based first person shooter game proposed by Pineda et al. [14] which uses information from the motor cortices of the brain to steer left/right, while forward/backwards movement is controlled by physical buttons. Another similar BCI system by Krepl [15] uses motor-control based on lateralized readiness potential (LRP) – a slow negative shift in the EEG over the activated motor cortex – for controlling the Pacman game. An example of P300 based games are Bayliss virtual driving task and a virtual apartment [16], [17] with highlighted red objects evoking a P300 when the user wants to make a selection.

Another recent P300 game is Finkes MindGame [18] were the P300 events are translated into movements of a character on a three-dimensional game board. SSVEP based games have been also designed based on subjects’ attention to a visual stimulus. In the Mind Balance game [19], a SSVEP is evoked by two different checkerboards with the participant’s attention focused in one of the two checkerboards to balance an avatar on a piece of string. An advantage of SSVEP over induced BCI paradigms is the multiple option selection by focusing attention on a stimulus. An example is the 2D racing game using SSVEP to control four different directional movements [20] in a similar way to how the FPS game was controlled in SSVEP BCI [21].

There are a lot of prototypes that use a multimodal approach by combining BCIs with other gaming controllers (i.e. keyboard, mouse, Wii controller, etc) [7]. A typical example of multimodal BCI system is the Bacteria Hunt game where the goal is of ‘eating’ as many bacteria as possible [22]. The user avatar is controlled using the keyboard whereas the amoeba is modulated by the user’s alpha activity (higher alpha results in more control). In the game ‘FindingStar’, users control the entities of the game using emotional signals coming from the BCI and use the mouse and the keyboard to defeat monsters and solve puzzles [23]. The ‘NeuroWander’ game uses the emotional and attentional states of the users to perform various quests and the navigation is performed using mouse and keyboard [24].

‘Affective Pacman’ was developed to investigate the frustration of users while playing a BCI game [25]. The game is controlled with two buttons that rotate Pacman. Frustration is caused by malfunctioning controls of the game. In another study, a steady-state visual evoked potential (SSVEP) based BCI, was used to control an avatar in the game ‘World of Warcraft’ [26]. To control the avatar, users had to control four icons. Three were used to have the avatar turn left, turn right and move forward and an-other one to perform certain actions such as grabbing objects and attacking other objects.

In another study, researchers used BCI technology to interact with mobile games [10]. A maze game with three different levels utilising meditative and attentive states was tested with 22 participants. Results indicated that the use of BCI technology with mobile games has the potential to offer new and exciting ways of game interaction. The MindFlex game is a commercial EEG-based BCI game played as a social activity at home [27]. The aim of the game is to interact with a floating ball around an obstacle course assembled on the game board. While these kinds of BCI techniques for controlling games are quite interesting, most of the games so far are proofs of concept. The interaction with these games is really slow, often with decreased game-play speed to allow for BCI control. This has an obvious impact on the average gamer, resulting in potential frustration and loss of engagement and interest.

3. The Roma Nova serious game

The aim of the Rome Reborn project was to create highly realistic 3D representations illustrating the urban development of
ancient Rome from the first settlement in the late Bronze Age (ca. 1000 B.C.) to the depopulation of the city in the early Middle Ages (ca. A.D. 550) [28]. The project includes hundreds of buildings, thirty-two of which are highly detailed monuments reconstructed on the basis of reliable archaeological evidence. The remainder of the 25–30 km² model are filled with procedurally-generated buildings based on accurate historical knowledge. Fig. 1 (left image) illustrates the northern side of the Roman Forum with the Curia Julia in the foreground, next to which is the Basilica Aemilia. In the distance is seen the Temple of the Divine Julius Caesar on the east side of the Forum plaza. The Curia was the principal place where the Senate met.

The interactive game (Fig. 1, right image) is built upon Rome Reborn and it is termed the Roma Nova project. It builds on previous work at Coventry University [29,30] and it is a serious game that aims at teaching history to children (11–14 years old). The game allows for exploratory learning by immersing the learner/player inside a virtual heritage environment where they learn different aspects of history through their interactions with a crowd of virtual Roman avatars. The game was built upon the ‘Unity 3D’ game engine using parts of the realistic reconstruction of ancient Rome. For the purpose of this work, both navigation and interaction is performed using brain-wave technology from the two headsets.

Players can interact with the serious game in three different ways according to the Levels of Interaction (LoI) framework [29,30]. LoI aims in simplifying the interactions between the players and automated ‘non-player’ characters. The first level of interaction offers a living background enhancing the player’s experience and immersion. At the second level of interaction characters are automatically provided with a more realistic graphic representation and more complex behaviours. Finally, at the last level of interaction, a conversational agent at the dialogue level appears as a more traditional way to teach the learner [30].

The implementation of the Roma Nova game that was integrated and tested with the two BCI systems includes: (a) a crowd of Roman characters in the Forum and (b) a highly detailed set of buildings that belong to the Rome Reborn model. Intelligent agents were wandering around in the gaming environment between predefined points of interest, whereas the player is able to move freely and is controlled via the BCI devices. To interact with the intelligent agents, the BCI-controlled player needs to approach them. Then, the intelligent agents change their current target to the position of the player, and hence start walking towards the player. When the intelligent agent is close enough to enter the dialogue level, a series of actions are triggered by the engine [30]: (a) an animation is triggered to change the camera from a wide angle to a close-up perspective; (b) the smoothed highly detailed version of the Roman character mesh is loaded to replace the low polygon version, along with the corresponding animations and (c) the steering controller attributed to every background character is dropped and replaced by a straightforward engine developed to play the scenario.

4. BCI interactions

This section presents the two different BCI devices that were used (NeuroSky MindSet and the Emotiv), the hardware configuration as well as the methods used for interacting with the serious game.

4.1. Hardware configuration

In terms of the hardware configuration, both prototypes used off-the-shelf hardware components. For the first prototype a laptop with a 64 bit Intel(R) Core(TM) 2 Duo processor T6600 at 2.2 GHz and 4 GB of memory was used in conjunction with the NeuroSky MindSet neuro-headset (i.e. one electrode at the FP1 position). The laptop was equipped with an NVIDIA GeForce GT 240 M graphics card. Standard laptop display technology, a 16' inch wide LCD has been used to display the serious game. The NeuroSky MindSet device is a complete headset with speakers and microphone transmitting data on Bluetooth. It allows extracting the ‘Attention’ and ‘Meditation’ levels of the user called “eSense Meters” [31] through the different EEG frequency bands by a black-boxed NeuroSky algorithm into an integer range of 0–100. The Attention is extracted through the modulation of the frequency band that is triggered by the intensity of a user's level of mental “focus” when user focuses on a single thought or an external object and decreases when distracted. On the other hand, Meditation levels increase when the user relaxes his/her mind and decreases when he/she is uneasy or stressed. The NeuroSky headset uses a single dry sensor attached to the forehead outside the cerebral cortex in the frontal lobe of the brain being responsible for the attention level and short-term memory tasks [32]. As soon as a connection between the Roma Nova game and the headset is established, it initiates a connection with the avatar and the simulation to send movement instructions.

Similar hardware components were used for the second prototype – with the main component being the Emotiv EPOC neuro-headset. A laptop with a 64-bit Intel(R) Core(TM) 2 Duo processor T7700 at 2.4 GHz and 4 GB of memory was used for the evaluation study. The laptop is equipped with an NVIDIA GeForce 8700 M GT graphics card. The Emotiv headset is a neuro-signal acquisition and processing wireless neuro-headset with 14 wet sensors (and 2 reference sensors) which is capable of detecting brain signals as well as user's facial expressions [33]. This requires a unique user profile to be created and train a classifier for the movement of the four directions based on user’s brain-patterns. The prototype system uses a combination of Cognitive and Facial/Muscular functions. The Emotiv Development Kit was used connecting the Emotiv EPOC headset to the Emotiv control panel to create and train a new user profile. The user is visualized by controlling an avatar in the serious game (Roma Nova). The raw data is calculated on the headset’s chip and sent to the dedicated computer in a 128 Hz frequency. Afterwards the software generates the keystroke events moving the player based on the users’ brain-activity and facial expressions.

Fig. 1. Left image: Rome Reborn reconstruction [28], Right image: Roma Nova game in action.
4.2. Avatar interaction

Both systems are capable of fully controlling the avatar even if they have a completely different configuration and numbers of sensors. As mentioned before, the NeuroSky MindSet uses only one sensor so that main challenge was to ‘map’ the output of the device to the standard movements of an avatar within a computer game. Moreover, even if no prior training is required to capture data from the device, new users need to familiarise themselves with the device, to control their attention and meditation. As soon as the Roma Nova serious game establishes connection with the headset it initiates the simulation. Both ends of the connection can ‘open’ input and output streams and read/write data. The headset sends two integer values (in the range 0–100) to the game with a frequency of 128 Hz depending on the attention and meditation levels of the user. The meditation component indicates the level of a user’s mental ‘calmness’ or ‘relaxation’. Table 1 illustrates how these values were mapped to represent direction and speed of the avatar.

Players control the avatar by changing cognitive states such as meditation and attention. For example, to go right, they will try to concentrate as hard as possible, while to take a left, users have to defocus their attention. Going straight ahead is possible only by maintaining a balance between the two states. High levels of meditation will prompt the avatar to run, medium levels will cause it to walk, low levels will make it go backwards and extremely low levels of meditation will cause it to stand still. Table 1 illustrates the values that were assigned for controlling the direction and speed of the avatar.

On the other hand, the Emotiv prototype (Fig. 2) requires prior training to operate the device. Training an effective new user profile takes approximately 30–60 min depending on the adaptability of the user. However, training the profile is not an easy task and requires practise and familiarisation, especially when the user needs to train more than two actions as it is easy to get distracted from outside stimuli and ‘confuse’ the training process of the user’s real ‘intentions’. In a training session of no more than 1 h, the classifier can be trained adequately for the forward & backward movements by using the Emotiv control panel [34].

New players can gain control over a single action quite quickly. Learning to control multiple actions typically requires practice and becomes progressively harder as additional actions are added. As players learn to train reproducible mental states for each action, the detection becomes increasingly precise. Most players typically achieve their best results after training each action several times. Overtraining can sometimes produce a decrease in accuracy – although this may also indicate a lack of consistency and mental fatigue. Practice and experience will help determine the ideal amount of training required for each individual user to successfully interact with the serious game [34]. As soon as the profile is created, then the combination of Cognitive and Facial/Muscular functions were used to control the avatar in the Roma Nova Game. In particular to go forwards or backwards cognitive functions were used. To turn left or right the Facial/Muscular functions were used such as eye blinking.

5. User study

This section presents the procedure followed for the evaluation together with the qualitative and quantitative results of both studies as well as a comparative study.

5.1. Participants and procedure

The testing was performed in open-space laboratory conditions and conference demonstration areas. Sixty-two participants took part in the user study. It was ensured that each participant was comfortable and at ease prior to the start of the experiment. Even if pulse rates or stress levels were not evaluated, each participant was asked to sit-down and a briefing was provided allowing them to be as calm and relaxed as possible.

For the NeuroSky prototype participants were allowed five minutes to accommodate with controlling the avatar and around three minutes to complete the task of arriving at a particular destination. The prototype was used by 31 users, across the span of two months (see Fig. 2). In particular, it was tested at Coventry University computer games laboratory, at the third Phoenix Partner Annual conference (which took place at Coventry University) as well as at the Archeovirtual 2012 International conference (which took place at Paestum, Italy, 15–18 November 2012). The participants were selected via random sampling to generate a non-biased set of results from a section that is more representative of the population. The dominant age group of the sample was 18–25 (74.19% of the total sample), consisting of 60.65% male participants and 39.35% females.

For the Emotiv prototype, 31 users were asked to provide comments on a questionnaire anonymously after playing the serious

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Controlling the direction and speed of the player (avatar).</th>
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<tbody>
<tr>
<td>Attention (0–100)</td>
<td>Direction</td>
</tr>
<tr>
<td>0–40</td>
<td>Turn left</td>
</tr>
<tr>
<td>40–75</td>
<td>Go straight ahead</td>
</tr>
<tr>
<td>75–100</td>
<td>Turn right</td>
</tr>
<tr>
<td>Meditation (0–100)</td>
<td>Speed</td>
</tr>
<tr>
<td>0–30</td>
<td>Stand still</td>
</tr>
<tr>
<td>30–50</td>
<td>Go backwards</td>
</tr>
<tr>
<td>50–70</td>
<td>Walk</td>
</tr>
<tr>
<td>70–100</td>
<td>Run</td>
</tr>
</tbody>
</table>

Fig. 2. Ability to control events using the Emotiv device.
The testing was performed an open-space environment at two locations at Coventry University: the Serious Games Institute (SGI) and the Department of Computing. Summarising the data samples from the users, descriptive statistics have been generated to quantify the experience. The sample consisted of 67.7% male and 32.3% females with a dominant age group of 18–25. The questionnaire used a Likert scale ranging from 1 to 5.

All users were given a participant information leaflet to read beforehand and a consent form to fill in and sign. The user survey was designed to gather both quantitative and qualitative data. Quantitative data has been collected on questions that require the participants to answer using a Likert scale, whereas qualitative data was gathered through the means of open-ended questions. After going through the gaming scenario, each user was asked to rate their experience taking into consideration learnability of the interface using the game, satisfaction of the player, performance of the interfaces and effort put by the player. These questions were closely followed by open-ended questions that aim to collect data on the overall experience and potentially suggest improvements.

### 5.2. Qualitative results

All participants were asked to provide detailed comments on the questionnaire anonymously. Also an unstructured short interview took place in a light mood after the trial. These comments/suggestions may contribute towards future improvements of BCI.

With respect to the first prototype, participants were drawn by the ease of use of the BCI device for controlling the virtual character (avatar) via EEG technology. They viewed the concept as an interesting approach for future gaming scenarios, categorising the whole experience as challenging, enjoyable and engaging. In particular, most participants were immediately engaged with the game and they wanted not only to perform the task (move from one position to another), but to explore the whole virtual city of the Roma Nova game and interact with the artificial intelligent agents (which were controlled by the computer) to become more knowledgeable about the history of Rome.

Even though the game-play was generally seen as ‘fun and fascinating’, some were dissatisfied with the avatar movement accuracy, and this affected learnability. It is worth-mentioning that some participants were able to recognise some movement types better than others. Turning left and right (switching from a strong state of concentration to a more relaxed state) was reported as the most difficult part to manage. Some reported a lag of around 2–3 s between their intentions and the actual output. While some participants had some difficulty with estimating the degree to which they reached their goal, others were running the test later during the day compared to people playing the game in the morning hours which may have affected their ability to concentrate fully.

Some participants mentioned the need for an initial training, user-profiling period and in-game guide. They found it easy to use the device but much harder to adapt to it and felt it was hard to ‘train’ their brains to concentrate and meditate. Going backwards was not seen as a popular movement type amongst players and its removal was advocated. Seeing relevant feedback on the screen, apart from the actual character movement, was suggested as being highly beneficial to the experience. Also, they wanted the interface to show the actual measured data, to get real-time feedback and know what to do to attempt self-regulating the attention/meditation levels. A couple proposed the introduction of hotkeys that should facilitate what attention can measure and last but not least, the implementation of the concept using a different game was advised.

For the second prototype a very useful suggestion was made about the Graphical User Interface (GUI) of the game. Participants found it easier to focus on the GUI components instead of the virtual character to perform the required action. This might be a result of the training trial, in which the users had to push/pull a virtual cube and when entering the virtual environment they had to re-adapt to the new elements. This can be confirmed by reports that it was easier to move the avatar by concentrating on the cube from the training trial, than actually visualising the character movement through space.

In contradiction to NeuroSky, navigating into the game was much easier. It is a clear indication that it would be better for the training trial to include the components from the game for the user to familiarise. Alternatively, assistive GUI components might be a useful addition. Overall the experience was reported as quite engaging and interesting regardless of certain issues of response time and accuracy that other Natural User Interfaces (NUI’s) might have. As soon as the participants had an ‘effective’ trained profile, then the level interaction was very satisfactory thus improving the learning process in respect to the serious game. Furthermore, it was reported that people with more experience in computer games will have an easier time learning to use the interface due to the simulation and interaction required for a computer game. That experience makes it much easier to learn how to operate the interface.

In terms of possible improvements participants did not feel very confident with the initial training of the device to create a personalised user-profile. Some found it hard to train, especially when using the cognitive functions. This was expected since the Emotiv device requires training but it varies on the effectiveness of each person. Another issue that was reported had to do with the contact of the sensors in relation to the user’s heads. Moreover, some participants reported that after a few minutes of interaction they were getting tired. The tiredness increased after more than 30 min of usage. Some participants proposed the introduction of hotkeys that should facilitate what attention and meditation can measure and last but not least, the implementation of the concept using a different game was advised. Additional recommendations comprise of the incorporation of more sensors and maybe eye tracking technology in order to enhance movement accuracy (see Fig. 3).
5.3. Quantitative results

In this section the results of testing each device in terms of: learnability of the interface using the game (Learnability), satisfaction of the player (Satisfaction), performance of the interfaces (Performance) and effort required by the player (Effort) are presented. Table 2 presents an overview of all the relevant statistics which are presented in further detail below.

Table 2
Relevant statistics for the NeuroSky and Emotiv based on questionnaire response.

<table>
<thead>
<tr>
<th></th>
<th>Learnability</th>
<th>Satisfaction</th>
<th>Performance</th>
<th>Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mann–Whitney U</td>
<td>185</td>
<td>207.5</td>
<td>211.5</td>
<td>259.5</td>
</tr>
<tr>
<td>z</td>
<td>-4.376</td>
<td>-4.046</td>
<td>-3.957</td>
<td>-3.271</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Mean NeuroSky</td>
<td>2.5161</td>
<td>4.4516</td>
<td>2.4516</td>
<td>3.8065</td>
</tr>
<tr>
<td>Mean Emotiv</td>
<td>3.6774</td>
<td>3.4516</td>
<td>3.5806</td>
<td>3.1290</td>
</tr>
</tbody>
</table>

Fig. 4 shows distribution of responses for Learnability. For Learnability, Kolmogorov–Smirnov was significant for both groups $D(31) = 0.25, p < 0.001$, for NeuroSky and $D(31) = 0.21, p < 0.001$ for Emotiv indicating a non-normal distribution. Due to the lack of normal distribution and the relatively low number of samples ($N = 62$) the non-parametric Mann–Whitney test was used to test for significance in this case and those below (Kolmogorov–Smirnov is reported for all cases). For Learnability the NeuroSky data (mean = 2.561) was considered significantly different from Emotiv data (mean = 3.667) $U = 185, z = -4.376, p < 0.001$. Emotiv is considered to be performing better in this case by a significant amount.

Fig. 5 shows distribution of responses for Satisfaction. For Satisfaction, Kolmogorov–Smirnov was again significant for both groups $D(31) = 0.25, p < 0.001$ for NeuroSky and $D(31) = 0.25, p < 0.001$ for Emotiv indicating the distribution of this variable was not normal. For Satisfaction the NeuroSky data (mean = 4.451) was considered significantly different from Emotiv data (mean = 3.667) $U = 185, z = -4.376, p < 0.001$. Emotiv is considered to be performing better in this case by a significant amount.
3.451) $U = 207.5$, $z = -4.046$, $p < 0.001$. For Satisfaction the NeuroSky performs better.

Fig. 6 demonstrates the distribution of responses for Performance. For Performance, Kolmogorov–Smirnov was significant $D(31) = 0.23$, $p < 0.05$ for NeuroSky and $D(31) = 0.26$, $p < 0.001$ for Emotiv, indicating the data did not belong to a normal distribution. For Performance the NeuroSky data (mean = 2.451) was considered significantly different from Emotiv data (mean = 3.580) $U = 211.5$, $z = -3.957$, $p < 0.001$. For Performance, these results indicate that the Emotiv performs significantly better than the NeuroSky.

Fig. 7 illustrates the distribution of responses for Effort. For Effort, Kolmogorov–Smirnov was significant $D(31) = 0.30$, $p < 0.001$ for NeuroSky and $D(31) = 0.27$, $p < 0.001$ for Emotiv, indicating the data was not normally distributed. For Effort the NeuroSky data (mean = 3.807) was considered significantly different from Emotiv data (mean = 3.129) $U = 259.5$, $z = -3.271$, $p < 0.01$. For Effort, the participants considered the NeuroSky to require significantly more effort in the overall.

6. Conclusions and future work

This paper presented two different ways of fully interacting with the same serious game using non-invasive BCIs. Two different EEG-based BCI devices were used, one single dry electrode which requires no calibration and a second that needs some calibration classifier training in order to create a user profile using also 14 wet electrodes. Overall the results indicate that both BCI technologies offer the potential of being used as alternative game interfaces prior to some familiarisation with the device and in some cases some sort of calibration. It was clear that the Emotiv device was better for gaining knowledge about the History of Rome (which is the goal of the serious game) and thus preferred for serious games.

Specifically, as far as the qualitative feedback is concerned, both categories of participants enjoyed the interaction experience. They were all in favour of using EEG technology for controlling and interacting with games even if they stated that the technology is
not as accurate as alternative interaction devices (i.e. keyboard, mouse, joystick, etc). NeuroSky users found it easier to use the device but much harder to adapt to it. They felt it was hard to ‘train’ their brains to concentrate and meditate at their first attempt. However, after some self-training it is possible to improve performance considerably. This varies according to the user and more studies need to be performed on this issue. On the contrary, the Emotiv device proved to be more effective for controlling the avatar into the serious game and for learning on how to use the interaction device, whereas the NeuroSky device performed better in terms of satisfaction of the player. There were significant differences between the two devices for the four aspects of the questionnaire reported. Controlling the character using the Emotiv was considered less effort as expected due to the increased sensitivity of the Emotiv compared to the NeuroSky. The performance was also better for the Emotiv for similar reasons. The NeuroSky was considered more satisfying perhaps owing to the immediate use of it due to the lack of setup as compared to the Emotiv. Learnability was also considered better for Emotiv likely due to the same reasons as Performance and Effect.

Moving towards to out-of-the-box BCI Games, training and adaptation is required for both the user and the machine for a successful interaction. It is an iterative learning process in which two entities (humans and computers) are adapting in a closed loop with the serious game for optimising the following: (a) interaction experience from the human side and (b) predefined desired result on the computer side. We can construct this as three different parts: (a) the user, (b) the machine where the data acquisition and translation is taking place, and (c) game/virtual environment where actions are visualised and adapted to the internal elements of the game based on the inputs, closing the loop. From one side, while the user learns to operate the interface the game is adapted based on user performance and proficiency, on the other hand the translated electrophysiological data must be used in a meaningful way, minimising random actions that could trigger false feedback back to the user. Over time, the skill is honed; hence, the feedback must reflect the user's task in an appropriate way. As it was mentioned before, all current brain controlled games are proof of concepts and they do not satisfy the requirements to be treated equally as any other games. In order to be able to create a serious game controlled with such a unique interface, we have to create mechanisms that will ensure a successful interaction. This can be achieved through game design principles modified for brain-control, adaptive gameplay based on user performance, and mechanisms for engaging the participants to the process.

As a future step, further prototype developments could also include an analysis into how certain audio tracks can stimulate concentration/attention and inherently affect game-play. Additional recommendations comprise of the incorporation of more sensors and maybe eye tracking technology to enhance movement accuracy. More sophisticated non-invasive BCI devices equipped with more electrodes and sensors will be also used followed by another comparative study. This will allow for a further analysis based on the combination of different readings.

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