Serious game for real-time brain-computer interface training

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Abstract. This article presents the development of the serious game PROEZA, for training users of a brain-computer interface system for control a hand prosthesis. The document describes the integration of electroencephalogram signals captured by an Emotiv EpoC+ headband, with the Unity video game engine. Also, it is presented how control commands are generated for the video game and for a handheld prosthetic device from these signals, basis of brain-computer interface systems. In addition, a protocol for validate the skills of the users to control the signals of the brain-computer interface system is proposed, based on evaluations before and after to training in PROEZA. The experimental results, after tests carried out on 2 users, show that the proposed protocol promises to be an appropriate strategy to evaluate the ability of users to control the brain-computer interface system and opens up the possibility to develop multiple physical and neuro rehabilitation applications using of serious games.

1. Introduction
A brain-computer interface (BCI) is a system that combines hardware and software, with the purpose that a user can send commands to control computers, external devices and applications using their brain activity, allowing an alternative mode of interaction or communication channel [1–3]. BCI systems work primarily by electroencephalogram (EEG), a non-invasive technique that allows the recording of superficial brain activity from the use of electrodes on the scalp, which allows portability of BCI systems, user safety and low cost of implementation, compared to other non-invasive methods. [3,4].

EEG-based BCI systems have great potential in many applications [5–7], which can be divided into medical and non-medical [2]. Medical applications mainly include rehabilitation and control of prosthetic devices, medical diagnosis, assisted mobility, web and music browsers controlled by BCI and recognition of mental status. Non-medical applications include games and virtual reality [2]. However, some research integrates medical and non-medical applications under the concept of Serious Game (SG), for which the main purpose is to combine, both serious aspects such as teaching, learning, communication or information, with playful aspects of the video game [8].

Multiple investigations that relate SG to BCI are described. In [9] authors presents a tri-dimension (3D) virtual reality (VR) BCI video game to sustained attention training in children with attention deficit hyperactivity disorder (ADHD), while the research presented in [10] was intended to measure, confirm and compare the brain activity of beta waves when playing SG in 3D and two-dimension (2D). In [11] authors explored the correlation between game mechanics and executive functions in order to develop video games that allow the evaluation or improvement of cognitive ability. Similarly, [12] describes a multi-player 3D video game controlled by EEG related to 3 different levels of attention, in order to improve brain functions such as attention and cognition. A low-cost multimodal system that combines...
the use of video games for health and the analysis of biomedical signals to optimize the processes of physical and neuro rehabilitation is presented in [13]. A comparison of two different EEG-based BCI devices to completely control the same SG was presented in [14]. In contrast, in [15] authors examined the effect of the gaming experience on the ability to modulate brain patterns during motor image training and identified the elements that contribute to the high control of BCI.

Despite the development of BCI systems, research exposes multiple problems and challenges related to accuracy, speed, price, the number of degrees of freedom, ease of use and user training process [2,16]. Considering that several investigations have shown that BCI users can learn to control their brain activity through video games [4,15,17] and that BCI games can be a source of motivation to practice, this research presents a SG for the training of end users of BCI systems, as a first exploration aimed at users who need to control a hand prosthesis from brain signals. The design and development methodology of the PROEZA SG is described, as well as the integration of the EEG signals as control commands in the game and a validation protocol for BCI training from the SG is proposed.

2. Materials and methods

2.1. PROEZA serious game

PROEZA is a SG developed for training subjects in the use of a BCI system. The game is runner category and its genre is adventure and survival. The graphical user interface (GUI) of the SG consists of the game environment with 2 head-up display (HUD): a life bar (HUD located in the upper left area) and distance travelled (HUD located in the upper zone right), as shown in Figure 1. The ultimate goal of the player is to travel as far as possible during the game. The distance will be the indicator that determines the user's training.

To start PROEZA SG, the user must enter the name and select the character. In the game environment, the character meets different environments (beach, desert, jungle and aquatic) and 3 types of elements that affect his life (plants, animals and obstacles). The game consists of avoiding obstacles and defending against non-useful elements (poisonous plants and dangerous animals) by evasive actions (intentions of right and left movement) and collecting elements that are useful (healing plants or animal meat). When an obstacle enters the player's proximity, a red stripe appears as shown in Figure 2. If the player loses concentration and does not generate the control EEG signals that allow him to perform evasive actions, he will face obstacles and enemies that are in his path until he loses his health and dies.

A laptop with a Core i7 7700 processor at 3.60 GHz, 16 Gb RAM and Nvidia GTX1060 3 Gb video card was used in the PROEZA development process. The assets and logic of the SG were implemented with the Unity3D video game engine (version 2017.4.8) and Microsoft Visual Studio was used to edit the program code in C#.

2.2. Electroencephalogram signal acquisition

2.2.1. Hardware. For data acquisition, an EMOTIV EPOC+ portable EEG system was used. This system is characterized by its low cost (compared to other equipment), wireless connectivity and the non-use of electrode conductive gel, avoiding user discomfort related to its placement and use. The system consists
of a 14-channels headband EEG and 4 reference channels, located according to 10-20 Standard, as shown in Figure 3. The EMOTIV EPOC+ system has a bandwidth between 0.16 Hz and 43 Hz, an internal sampling frequency of 2048 Hz and 128 Hz per channel (MEMS sampling), with transmission to the software through a 2.4 GHz wireless connectivity (Bluetooth). Likewise, the device allows to obtain information of brain electrical impulses of the type Alpha (α), Beta (β), Theta (θ), Gamma (γ) and Delta (δ), as indicated [18].

![Figure 3. EEG electrodes location](image)

2.2.2. Software. EMOTIV PRO, an integrated software solution for neuroscience research and education was used to interact with the EMOTIV EPOC+. In addition, CORTEX software development kit (SDK) was used, like an application programming interface (API) for the headband. CORTEX supports Java, C#, C++, Python, Ruby, NodeJS, PHP and other programming languages, and is compatible with Mac and Windows.

2.3. Electroencephalogram signals integration in serious game

The integration of EEG signals into an SG allows the creation of a BCI system, which measures brain electrical activity and translates it into control commands for the video game engine to execute.

To couple the EEG signals as inputs for the SG, CORTEX API and its protocol consisting of three building blocks (JSON, JSON-RPC and WebSockets) were used. To start using CORTEX, the WebSocket plug-in and the JSON Object and Cortex-implementation-for-Unity repositories were required to facilitate the connection and communication process between the SG (UNITY game engine) and the EEG signals (EMOTIV EPOC+ system), similar to [20]. This connection through the WebSocket, allowed to form the BCI system and the SG could receive the mental commands associated with a specific movement intention.

| Table 1. Real-time command vocabulary for the SG controlled by EEG signals. |
|-----------------------------------------------|
| EEG control signal | Character action | Associated gesture |
| Intention of movement to the left | Move left | Clamp grip |
| Intention of movement to the right | Move to the right | Tweezer grip |
| No intention of movement (Neutral) | Do not make any lateral movements | Relaxed / open hand |

Considering that this research is a first exploration aimed at users who need to manipulate and control a hand prosthesis from brain signals, Table 1 describes the mental commands (movement intentions) associated with the PROEZA SG character's action and the gesture that replicates a virtual hand.
prosthesis (clamp grip, tweezer grip and relaxed hand). The process to obtain mental commands presented in Table 1 consists of the following steps:

- Log in to the cortex service.
- Authenticate a user in the application, create a session to start data logging.
- Subscription to the different service channels.
- Calibration of movement intentions (neutral, right and left). Once the calibration is done you can start the game.

2.4. Validation protocol

To validate the domain of the BCI system by the users of the SG, a protocol was proposed to evaluate the responses to visual stimuli after a training session. Therefore, the definition of the experimental design of the project focused on a study of the before-after type [21]. For the tests carried out, the EMOTIV EPOC+ electrodes were located according to the 10-20 standard (Figure 3). This location allowed to obtain information related to the areas of brain activity of the users, especially those related to the visual evoked potentials of (VEPs) [22,23].

To execute the validation protocol, a tool was developed that presents a BCI response evaluation interface (IER-BCI) and complementary to the PROEZA SG with BCI. The tests implemented in IER-BCI were aimed at measuring the response times of a user against visual stimuli, the amount of successes against decisions, and the holding time for an intention to move, similar to that proposed by [24]. The characteristics defined for these tests are following:

- Response time: It allows you to evaluate the response time against a decision factor, that is, the time elapsed from the moment a stimulus is presented until a decision is made (correct or wrong). 2 types of stimuli are used; therefore, the result is 2 types of decisions.
- Type of decision: In a sequence of decision factors, it allows to evaluate the level of success of the decisions taken, that is, it analyzes the number of successes against the actions that must be taken (3 types) when 3 types of stimuli are presented. These include the "rest" action for the "nothing" stimulus.
- Decision holding time: It allows to evaluate the time in which a decision is held, that is, the time of concentration in a specific decision.

The protocol considered all the phases of the test, from the installation, adjustments and calibration of the BCI device, followed by the initial evaluation with the IER-BCI tool, an intermediate training process with the PROEZA SG, until the final evaluation again with the IER-BCI tool, as presented in Figure 4. It was estimated that a work session with an approximate duration of 20 minutes per user, which could not repeat tests in the same session. Similar to that developed by [14] and [25], the protocol was deployed in a low noise and low visual disturbance test environment, with the test subject sitting in front of a computer.

![Figure 4. Validation protocol.](image-url)
2.5. Response evaluation software
IER-BCI is a simulation tool developed to evaluate a user's performance before and after a BCI training. The simulation, the user is presented with two types of objects, associated with an intention of movement: Bottle to clamp grip, and Pencil to tweezers grip, as shown in Figure 5(a), Figure 5(b), Figure 5(c) and Figure 5(d).

The first sequence consists of 5 objects for one gesture and 5 objects for the other. Each object appears on the screen for 10 seconds, until a decision of the user is obtained. If the intention of movement coincides with the current object, it disappears and a positive sound and visual reinforcement is generated, in addition to the feedback made by the virtual hand, as shown in Figure 6.

The next sequence presents 10 random objects with the same previous rules, adding the fact that a wrong gesture eliminates the object and gives a negative reinforcement, as shown in Figure 7.

As a final stage, the user has the possibility to choose any of the two intentions of movement, and must hold it for as long as possible, as presented in Figure 8. The object will be floating as long as the intention to move is held and, when a specific threshold is exceeded, the test will end.

The test data is stored in a comma separated values (CSV) file, which records the variables: User, Average reaction time, Number of hits and Time that sustains an action. This information allows the results of the BCI training to be compared over time.

![Figure 5. IER-BCI types of objects and intention of movement. (a) Object type bottle. (b) Object type pencil. (c) Clamp grip. (d) Tweezers grip.](image)

![Figure 6. IER-BCI correct intention of movement.](image)

![Figure 7. IER-BCI wrong intention of movement.](image)

![Figure 8. IER-BCI holding intention of movement.](image)

3. Results
Two test sessions (individual) of 40 minutes each were carried out. Two men of 27 and 36 years respectively, participated in the sessions held in a classroom of “Centro de Servicios y Gestión Empresarial (CESGE), Regional Antioquia”, of the “Servicio Nacional de Aprendizaje (SENA)”. Before the tests, each participant provided written informed consent, confirmed that their participation was voluntary and does not imply any cost or financial compensation and received a detailed explanation of the protocol.

In both tests the BCI system calibration was developed and the proposed validation protocol was followed. This allowed to evaluate the progress of the test subject, by comparing its performance before and after playing PROEZA. In Figure 9 the user is presented while performing the calibration stage. Experimental results showed that user performance improved with practice over time. From the beginning of the protocol, the criteria of average reaction time, number of successes in the decisions
taken, and time of support in a given action were evaluated. In Figure 10 and Figure 11 the development of the validation and training processes respectively is presented.

Additionally, the process allowed evaluating aspects of user experience (UX) of SG. It was found in all cases that users presented discomfort with prolonged use (greater than 30 minutes) of the BCI device due to the pressure it generated on the scalp. Likewise, users were receptive to the interface of the SG and the IER-BCI tool, however, they expressed difficulty in mastering a second control action with the BCI device. That is, after training and mastering a control action, the training and recognition process of a second action was complex and a large part of the BCI device's responses were directed to the first trained, even when the users stated that they were looking to execute the second action.

4. Conclusions
This article presented a video game for the training of end users of BCI systems, taking into account that games can be a source of motivation to practice, becoming a useful tool in the BCI user training process.

PROEZA SG was designed and developed and the integration between the EEG signals (acquired by a low-cost device) and the video game was described, which allowed the formation of a BCI system. Based on the above, a scenario was created where the user controls the direction (right, left and neutral) that the character takes in the SG feat, using his intentions of movement. During the game, the user can observe a gesture associated with the direction he took, which is related to the position of the hand (spherical grip, calliper and relaxed / open hand). The scenario created includes a training protocol for BCI end users.

Experimental results show that the proposed protocol promises to be a strategy to validate training from the SG. In the use of BCI devices it is necessary to define an initial adjustment protocol for it, in order to maximize the UX. Additionally, the results highlight that a BCI can be viable, even using a low cost EEG signal acquisition system, making it possible for BCI technology to be accessible and used in applications, games and virtual reality.

As future work, we intend to carry out experiments on a greater number of test subjects with and without motor disabilities, as well as using usability evaluations or other complementary metrics related to the user experience or the validation of the BCI user training and training process.

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