

# A General Model for Electroencephalography-Controlled Brain-Computer Interface Games

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**Abstract.** The rapid expansion of Brain-Computer Interface (BCI) technology allowed for the recent development of applications outside of clinical environments, such as education, arts and games. Games controlled by electroencephalography (EEG), a specific case of BCI technology, benefit from both areas, since they can be played by virtually any person regardless of physical condition, can be applied in numerous serious and entertainment contexts, and are ludic by nature. However, they also share the same challenges of design and development from both fields, especially since they demand numerous specific and specialized knowledge for their development. In this sense, this work presents a model for games using EEG-based BCI controls. The proposed model is intended to help researchers describe, compare and develop new EEG-controlled games by instantiating its abstract and functional components using concepts from the fields of BCI and games. A group of EEG-controlled games from the literature was selected to demonstrate the usefulness and representativeness of the model. The demonstration showed that an overview classification and the details of the selected games were able to be described using the model and its components.

**Keywords:** BCI · EEG · Game · Model · HCI

## 1 Introduction

The recent evolution of Brain-Computer Interface (BCI) technologies allowed the development of novel applications both for clinical and domestic environments [4]. Games based on electroencephalography (EEG)—a specific case of non-invasive BCI—are being increasingly developed and applied in both contexts, especially because they can be played potentially by any person regardless of physical impairments, as the EEG signals are read and translated by the application directly from the brain [30,31].

In this context, EEG-based BCI are usually employed in serious games, which are developed and used for any purpose other than (or in addition to) entertainment [12]. These games have potential to be employed in many different fields

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and applications, such as being a treatment option to help patients in rehabilitation [15] and training cognitive functions through neurofeedback [6,28,29]. However, given the evolution of BCI algorithms and the emergence of consumer-grade EEG devices, these games are also starting to be developed to be used solely for entertainment purposes [27], benefiting both healthy and impaired players.

The development of BCI games raises challenges that are related to both fields [9,24]. From the perspective of BCI, the developer must ensure that the system is precise enough to capture, process and identify the target neural mechanism (and thus, the player's intention) accurately in real time. From the perspective of games, the developer must also ensure the game flow, so that the player is immersed into the game, have fun playing it and desire to play it again, even if its purpose is not solely entertainment. Thus, it is required domain over knowledge from many different areas that are related to both games and BCI, including Neurophysiology, Psychology and Human-Computer Interaction (HCI).

Existing models and representative schemes from the literature can describe specific aspects of BCI-based systems or games, in both general and specialized contexts. However, these models can only represent EEG-controlled games as a BCI system or as a game—not as a whole, single entity. To our knowledge, there are currently no model for representing EEG-controlled games and the specific components, attributes and features that constitute them. In this sense, the main objective of this work is to describe a general model for EEG-controlled games, and to demonstrate the usefulness and representativeness of this model with BCI-based games from the literature. The proposed model intends to unite concepts and vocabulary from both fields into a single theoretical framework.

This work is organized as follows: Sect. 2 presents the related work, including other models and how they are related to our study; Sect. 3 describes the proposed model and its development process; Sect. 4 presents a demonstration of the model using games from the literature; Sect. 5 discusses the results of the demonstration and the implications of the model for the literature; and Sect. 6 concludes the paper.

## 2 Related Work

The related works present models, frameworks and/or conceptual schemes regarding games, BCI systems and BCI-based games. For both fields, there are examples of abstract models and frameworks for representing those systems in a general or specific manner, given that they can be applied in a number of different contexts depending on their purpose. It is reasonable to assume that there is a higher number of models for representing games, given that the field of games is relatively older than the field of BCI. We will focus on describing those that are closely related or pertinent to the scope of this work.

For the field of BCI, the studies from Mason and Birch [19] and Mason et al. [20] are closely related to the scope of our work. In the model presented by

Mason and Birch [19], which was derived using concepts from related fields such as HCI, the BCI system was described based on its functional components, and was employed as a base for constructing a framework and a taxonomy for BCI design. This model and taxonomy were later updated and expanded by Mason et al. [20], using the Human Activity Assistive Technology model as base for its construction. Thus, this model considers BCI systems as an assistive technology, focusing on people with functional limitations that uses these systems to overcome an ability gap and perform an action in the environment.

More recently, Kosmyna and Lécuyer [11] presented a conceptual space for EEG-based BCI systems. The authors described key concepts of BCI systems and their possible values, divided into four axes with nine sub-axes. These axes represent information about *when* the BCI system is used (i.e., the temporal features of the BCI system, such as whether its commands are employed actively or passively by the user); for *what* it is used (its application and employed neural mechanism); *how* it is used (multi-modal aspects of the system); and *where* it is used (virtual, physical or mixed environments). The authors demonstrate their conceptual space by instantiating a set of BCI-based systems from the literature, and found that most systems are based on virtual environments, using event-related (de)synchronization as neural paradigm, and are synchronous (the user must wait for a trigger to use a BCI command).

As stated in Sect. 1, BCIs are usually (but not exclusively) employed in serious games, given the intersection of contexts and applications for both fields. Models and classification schemes for serious games are presented, for example, in the works of Djaouti et al. [2] and De Lope and Medina-Medina [17], which present taxonomic schemes for representing and classifying serious games, while McCallum and Boletsis [21] present a classification scheme for the specific case of serious games for dementia. Considering both fields, there are also studies that focus on representing BCI-based serious games. Sung et al. [24], for example, present a methodology and development architecture for creating new EEG-based serious games, which define roles for experts, game developers and designers in the development process and unify methodologies from both fields.

Although these models can represent a wide variety of BCI-based systems and their related concepts, to our knowledge there are currently no models for representing the case of EEG-controlled games. The BCI models presented in the literature can represent systems in a general manner and as a special case of assistive devices. However, specific components related to the game part of the system may be lost in this context. In the same sense, models for representing games, both general and specific, are not able to represent the components related to the capturing, processing and application of EEG signals from the user to the game. In this context, the model proposed in this work draws inspiration from related works of both fields, and was developed to close the gap between BCI and game systems by representing both as only one entity.

## 3 Model for EEG-Controlled Games

In this section the proposed general model for EEG-controlled games is presented, including its development process and how its final version was derived.

### 3.1 Development Process

The model was constructed for representing virtually any kind of game that is controlled in any aspect using EEG. The main principles (p$x$) that guided the construction of the model were that:

p1. The BCI system and the game system should be as less dissociated as possible;
p2. The model should be general enough to represent as best as possible any EEG-controlled game currently available in the literature; and
p3. The model should be expandable and adaptable for specific situations and contexts.

As the model is intended to represent EEG-controlled games, theoretical knowledge from classic BCI works [19,20,31] and the analysis of various BCI games from the literature [3,4,27], in addition to previous experience on both the development and evaluation of such games [26,28–30], served as the foundation for constructing and refining the model. After the derivation of its initial version based on related models as described in Sect. 2, the model was refined in an iterative, incremental process of fitting games obtained from the literature in its components, and thus identifying missing, important components that could help describing those games more accurately. This general development process is illustrated in Fig. 1, and the logic that guided its derivation is described next.

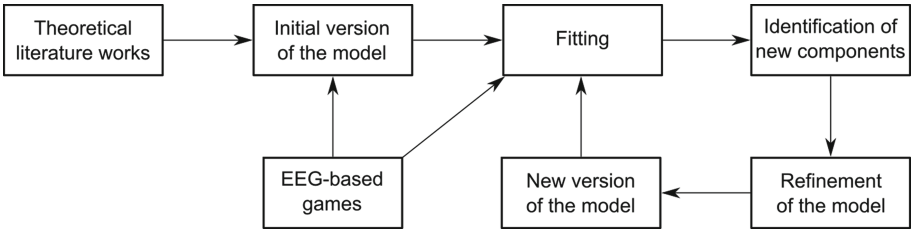



**Fig. 1.** Development process of the model.

### 3.2 Model Derivation and Construction

The model itself is based on the classical closed-loop neurofeedback scheme for BCI-based systems (Fig. 2). In this scheme, the BCI system is de-composed into six main steps representing its function: data acquisition, pre-processing, feature

extraction, feature classification/translation, application, and (neuro)feedback [31]. This scheme is largely seen in a number of primary works, in which the BCI system architecture is based or adapted from it (e.g., Hasan and Gan [7], Koo et al. [10], Lalor et al. [14], and Tangermann et al. [25]), and resembles other BCI-based models, such as the functional model of Mason and Birch [19].

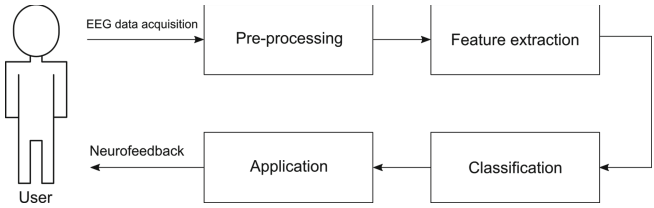



**Fig. 2.** Classic closed-loop neurofeedback architecture.

In a general sense, the classic BCI system can be seen as a filter (or transducer), receiving and transforming an input signal (the EEG data from the user) into an output control signal (for the application to consume). The target application then feeds the results of this control signal back to the user, which in turn consciously or unconsciously alters his/her brain electro-chemical dynamics in response, and this change is then captured by the EEG acquisition device, composing the closed-loop architecture. Thus, the classic BCI closed-loop architecture scheme from Fig. 2 can be simplified into the following model:

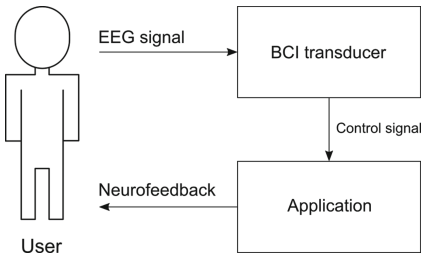



**Fig. 3.** Simplified closed-loop neurofeedback model.

In the proposed model, based on the model presented in Fig. 3 and in the context of games, the target application is the game itself, being directly or indirectly controlled by the control signal provided by the BCI transducer. The model is derived by an even more simplified scheme (Fig. 4), in which the game and the BCI transducer are seen as only one entity (based on principle p1 of the model): the EEG-controlled game, which receives an input from the player, and provides a feedback based on its current internal state.

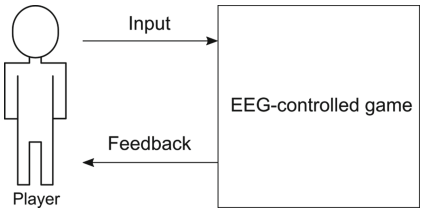



**Fig. 4.** Simplified EEG-controlled game model.

It is important to notice that, in this simplified scheme, the input is not restricted to an EEG signal, nor is the feedback restricted to a neurofeedback itself. The reason is that, in the context of games, the application can be controlled not only by the EEG signals, but by other forms of controls as well, such as physical ones (e.g., mouse, keyboard, joysticks and gamepads) or other physiological ones (e.g., heart rate, breathing rate and electrodermal activity)[1]. In the same context, the feedback provided by the game can not only represent the response to the EEG-based control, but it can also represent the changes in the game world (and in the objects contained in this world) that were caused both internally by game itself, and externally by the physical and/or physiological controls from the player(s).

These details are fundamental for the detailing of the model. Every component of the simplified model can be further decomposed into several parts: The input is composed of the EEG input and other physical/physiological inputs; the feedback is composed of both the feedback from the game's virtual interface and/or the neurofeedback; and the EEG-controlled game is an implementation that contains the game logic, including the control mechanics and the game world, and an interface to receive the input(s) and to provide feedback to the player. This more detailed model is represented in Fig. 5.

In this model, the optional components are marked with non-continuous lines. The presence of optional components contributes for a more adaptive scheme (based on principle p3 of the model). Here, the other physical and physiological inputs are optional, as the model represents and focus on EEG-controlled games. The control interface receives the input and translates it into control signals, which are employed as control mechanics in the game logic to alter the game world. This change in the game world reflects on the virtual interface, which presents its state to the player in the form of a feedback. This feedback can be visual, auditory or somatosensory (haptic/vibrotactile or thermal). Although the virtual feedback is always present, as it represents the game environment and the status of the game to the player (assuming that a player cannot play a game without knowing at least its status in a finite amount of time), the

[1] This is also the reason that the game component is referred as "EEG-controlled" rather than "EEG-based" in this work, as the first term is a generalization of the latter, i.e., it can represent any game that is controlled by EEG, including those that are based solely on this kind of control.

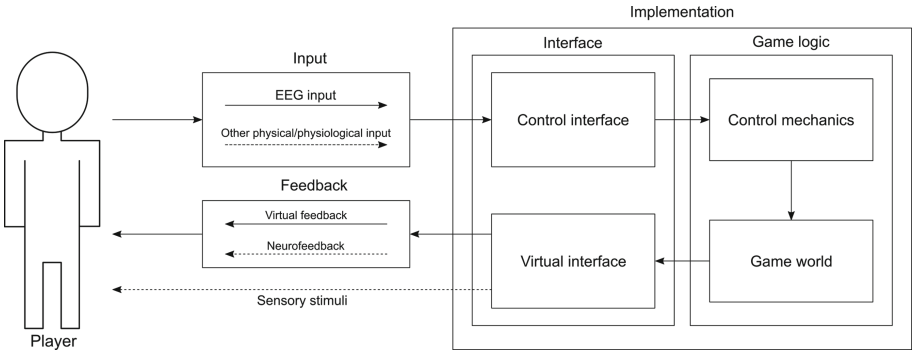



**Fig. 5.** Detailed EEG-controlled game model.

neurofeedback is optional, as the game can be played using a passive BCI (e.g., passively adjusting the game difficulty using the player's emotions), and thus no neurofeedback is explicitly provided. The sensory stimuli is another optional element which was introduced based on both principles p2 and p3 of the model, as specific control signals (e.g., SSVEP and P300) require an external stimulus to be generated and captured by the EEG acquisition device.

Finally, the detailed model presented in Fig. 5 can be further detailed to represent all components of an EEG-controlled game. This allow for the instantiation of each of these components in a very specific sense, as opposed to a more abstract model. This complete general model can be seen in Fig. 6.

In the complete model, the EEG input is captured in the data collection step by **sensors** connected to an **EEG device**, which transfers the acquired EEG data to the BCI module in the **control interface** for the processing of this data. This include the classic steps in a BCI system, i.e., pre-processing, feature extraction, classification, and sending the classified control signal to the application, i.e., the game. In cases where there is no need for a classifier, in which the system translates the signal's extracted features directly to a continuous variable to be employed by the game (e.g., applying the theta/beta ratio to calculate the players' level of attention), the module transmits the processed feature translation directly to the game after the feature extraction step. There can also be an intermediate, optional step for feature selection before the actual classification, usually employed to increase the classifier's accuracy.

The received **control signals** are then employed as **control mechanics** in the game logic, altering the **game world** and its components, i.e., the **game environment**, and eventual player characters, game objects and Non-Playable Characters (NPCs). Every component in the game world, with exception of the game environment, are optional, as a game can be designed with or without objects and characters, but not without an environment in which the game logic occurs and that the player can interact with it in any manner. If exists, the **player character** can interact with both the environment and its objects and with other non-playable, computer-controlled characters, or even with other

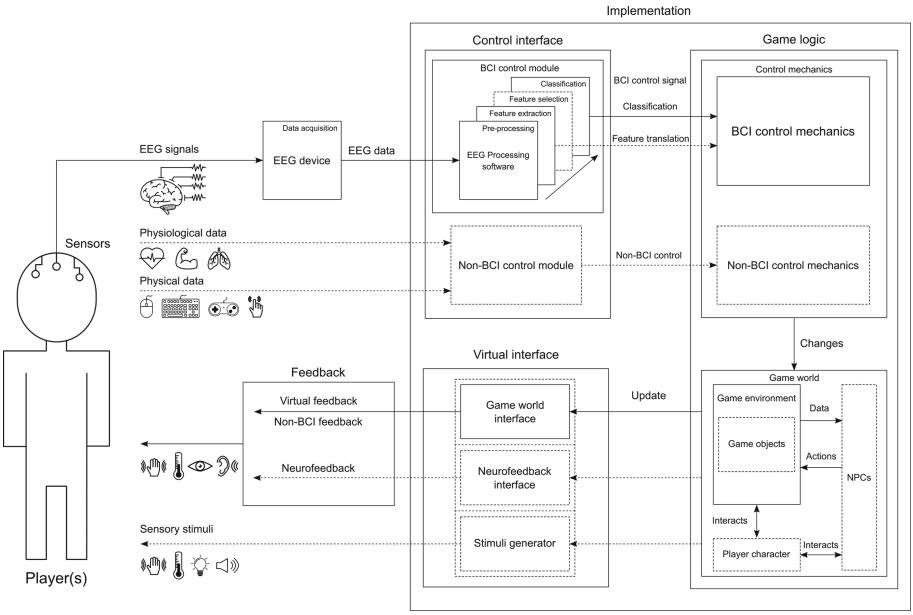



**Fig. 6.** Complete general EEG-controlled BCI game model.

player characters, in the case of multiplayer games. The **NPCs**, while being agents, can perceive the environment and perform actions in this environment in response to this data.

In the same sense, the other **physical and physiological** data, labelled as "Non-BCI" for a more general term, are handled by their own modules and control their own mechanics within the game logic. They are also optional components, given that the game can be designed to be controlled solely with EEG controls. All these changes, performed by the player or by the game itself, are then updated in the game's **virtual interface**, which is composed by the game world interface, the neurofeedback interface and the stimuli generator.

The **game world interface** is used to represent all components of the game world, including the player character and the NPCs. This interface can contain the neurofeedback interface and the stimuli generator, or these components can be separated, having their own interfaces (e.g., the stimuli generator or the neurofeedback can be contained in a separate screen or a device connected to the subject's body). While the game world interface and the **neurofeedback interface** provide feedback for the subject, the **stimuli generator** provides a sensory stimulus, in accordance with the model in Fig. 5. All the components and their description are summarized in Table 1.

## 4 Model Demonstration

The method to demonstrate the model is similar to the approach employed by Mason and Birch [19] and Kosmyna and Lécuyer [11], by means of demonstrating its usefulness through the representation of a set of works that describes EEG-based systems/games using the model, and instantiating each of its components. Tables 2 and 3 present the result of this demonstration, with games presented in alphabetical order.

Games were selected from studies using different game genres, control styles and EEG-based control signals to provide more diversity in the data. All positions in the Sensors subcomponent are based on the 10–20 international system [27] and its extended versions. Optional values that were not present in the game were marked as "N/A" (not applied).

## 5 Discussion

The demonstration of the model wielded some interesting results about its ability to represent and compare games from the literature. The individual representation of each game gives an overview of its contents and allow for the extraction of its concept and design from this description. The open aspect of the description of each component, as opposed to more closed and pre-defined classification values, also gives the researcher or developer more freedom to emphasize on specific aspects that s/he finds pertinent. Thus, although a brief summary of each component was provided for each game for the purpose of demonstrating its representativeness, a more detailed description is also possible.

In comparison to other models from the literature, the proposed model represents the BCI aspect of the game in a similar fashion to most representative schemes of EEG-based systems, as it is based on the classic neurofeedback loop and presents the same EEG signal processing steps. It has the advantage, however, of also representing the details about the game itself, as both aspects are seen as only one entity, in contrast with other BCI models and representations in which the BCI implementation is taken as a separate software or hardware, or in which the game (or any other application) is abstracted and only receives the control signal to consume. The downside of this generalist approach for the representation of games is that some details about its implementation (including the implementation of the BCI module) may be lost, e.g., in which platform the game is intended to run, its genre, the details of the feature extraction and translation steps and so on.

However, although not exhaustively shown in the demonstration, some specific details about the signal processing algorithm could also be represented in the *BCI Control* component depending on the goals of the researcher. Information about the pre-processing steps (e.g., filters and de-noising techniques) or the feature extraction/classification algorithms could help in the comparison of different implementations for the detection and employment of the same neural mechanism. The same could be applied to game-related components, such as

**Table 1.** All model's components and their description.

| Component | | Description |
|---|---|---|
| **EEG data collection** | **Sensors** | The type and amount of sensors that were employed to capture the player's EEG data. In the case of EEG, active or passive electrodes are usually employed. These electrodes can be wet (i.e., they require a saline or conductive substance to help lowering the impedance) or dry, and are generally placed strategically on the scalp depending on the neural mechanism that the researcher intends to identify. |
| | **EEG device** | The biosignal amplifier and/or head-mounted device that was employed to receive the EEG data from the sensors. The captured data is usually amplified and pre-processed before being used by the feature extraction and/or classification algorithm. Depending on the device (e.g., consumer-grade EEG devices), the device can also perform the pre-processing and feature extraction/classification steps. |
| **Control interface** | **BCI control signal** | The EEG-based control signal or underlying neural mechanism that was employed as a control command to the game. Examples of these control signals are the SSVEP, P300, motor imagery, and cognitive states, such as attention, relaxation and emotions. |
| | **Non-BCI control** | Any other non-BCI control, such as physical/analogical/digital controls (e.g., mouse, keyboard, joystick) and other biophysical signals (e.g., EMG, EOG, ECG). |
| **Control mechanics** | **BCI** | How the EEG-based control is employed to change or to interact with the game world. This include moving or acting with a game character, interacting with objects and/or non-playable characters from the game world or altering the game environment. |
| | **Non-BCI** | Similar to the BCI control mechanics, but applied to other, non-BCI controls, if they exist. |
| **Game world** | | The game world is composed of its **environment**, and eventual **player characters**, non-playable characters (**NPCs**) and **game objects**. Depending on the game rules, the player can act through a player character or directly to the game and its objects. |
| | **Player(s) character(s)** | The players' controllable characters in the game world (if it exists), including its amount (single player, multiplayer), and how the player interacts or controls it. |
| | **Environment** | The environment that the game takes place. This environment can be virtual (i.e., in a virtual, simulated world) or physical (i.e., in the real world, using physical objects or machines). |
| **Virtual interface** | | The virtual interface is responsible for providing the player(s) with feedback from the game, as well as external stimuli and neurofeedback. This include the **game world interface**, responsible for the **virtual feedback** that updates the player about the status of the game world; the neurofeedback interface; and the stimuli generator. Note that the latter two can both be included in the game world interface, or be separated (e.g., an external device used to generate visual or auditory stimuli that is separated from the game screen). |
| | **NF interface** | Provides the specific feedback that updates the player about his/her internal mental state and/or regarding the result of the signal processing algorithm. This can be, for example, a numerical value, a change in the virtual interface (e.g., an interface element that visually changes according to the classification result, or the movement of an object/character in the game world), a sound, a vibration etc. Note that this feedback may also be embedded in the virtual feedback. |
| | **Stimuli generator** | Generates external stimuli to evoke specific brain responses, which are required for exogenous control signals (e.g., P300 and SSVEP). These stimuli can be visual, auditive or somatosensory (e.g., thermal and vibrotactile). |

**Table 2.** Demonstration of the model and its components.

| | | |
|---|---|---|
| | **αWoW [13]** | |
| EEG data collection | **Sensors:** | Four wet electrodes, placed at positions P1, P2, CP7, and CP8. |
| | **EEG device:** | An Emotiv Epoc. |
| Control interface | **BCI control:** | Relaxation level, calculated using a FFT of the α frequency band. |
| | **N/BCI control:** | Mouse and keyboard. |
| Control mechanics | **BCI:** | Activates a specific ability that the player can cast to change the shape and powers of its avatar. |
| | **Non-BCI:** | Controls the movement of the character and the casting of abilities. |
| Game world | **Player character:** | A humanoid avatar that can shape-shift into a bear. |
| | **Environment:** | Virtual, three-dimensional, multiplayer open world. |
| Virtual interface | **World interface:** | PC monitor display, with a three-dimensional view of the world and third-person view of the player character. |
| | **NF interface:** | Embedded in the game's graphical interface. A bar with a numerical threshold value that indicates whether the player reached the required cognitive state to activate the related ability. |
| | **Stimuli generator:** | N/A. |
| | **Aiming Game [8]** | |
| EEG data collection | **Sensors:** | Not informed (up to 14 saline electrodes, given the employed device). |
| | **EEG device:** | An Emotiv Epoc. |
| Control interface | **BCI control:** | Emotion (arousal), represented with a value ranging from 1 to 5. |
| | **N/BCI control:** | Mouse. |
| Control mechanics | **BCI:** | Dynamically adjusts the game difficulty, distorting the aim and blurring targets. |
| | **Non-BCI:** | Used to point and click the target airplanes in the screen. |
| Game world | **Player character:** | N/A. |
| | **Environment:** | A virtual, 2-dimensional picture of the sky, with moving targets. |
| Virtual interface | **World interface:** | A PC monitor screen, showing the virtual environment and the player's aim. |
| | **NF interface:** | A bar, divided into five segments, shows the player's current level of arousal. |
| | **Stimuli generator:** | N/A. |
| | **BrainArena [1]** | |
| EEG data collection | **Sensors:** | Two GAMMACaps with eight active electrodes positioned over the parietal region. |
| | **EEG device:** | Two g.USBAmp amplifiers. |
| Control interface | **BCI control:** | Motor imagery, classified using a LDA classifier with band power features extracted using CSP filters. |
| | **N/BCI control:** | N/A. |
| Control mechanics | **BCI:** | The player must perform the indicated imagined movement to move a ball into the target goal. |
| | **Non-BCI:** | N/A. |
| Game world | **Player character:** | N/A. |
| | **Environment:** | A black scenario with three feedback gauges, two goals, a ball and instructions for the current imagined movement to be performed by each player. |
| Virtual interface | **World interface:** | A PC monitor screen, showing all elements of the game world for both players. |
| | **NF interface:** | Three feedback gauges in the game screen indicating the intensity of the recognized motor imagery command (left, right), one for each player and one for the cumulative result of the identified imagined movements. |
| | **Stimuli generator:** | N/A. |
| | **Connect Four [18]** | |
| EEG data collection | **Sensors:** | Nine silver chloride electrodes. |
| | **EEG device:** | A 32-channel ActiCap system with a BrainAmp amplifier. |
| Control interface | **BCI control:** | P300, calculated with a bayesian classifier after spatial and temporal filtering. |
| | **N/BCI control:** | N/A. |
| Control mechanics | **BCI:** | Used to select a target column in a game of Connect Four with two players. |
| | **Non-BCI:** | N/A. |
| Game world | **Player character:** | N/A. |
| | **Environment:** | A virtual, two-dimensional Connect Four game board. |
| Virtual interface | **World interface:** | PC monitor display showing the board and the time left to make a move. |
| | **NF interface:** | A rectangle appear over the selected column to indicate the classification result. |
| | **Stimuli generator:** | Each column of the game board flashes in sequence to evoke the P300 potential. |
| | **Hangman BCI [7]** | |
| EEG data collection | **Sensors:** | Nine electrodes, positioned over the sensorimotor cortex. |
| | **EEG device:** | A 64+2 channel Biosemi cap. |
| Control interface | **BCI control:** | Motor imagery, using a LDA classifier as a initial state for a GMM algorithm. |
| | **N/BCI control:** | N/A. |
| Control mechanics | **BCI:** | Used to move the cursor (left/right) and select a letter in a Hangman game. |
| | **Non-BCI:** | N/A. |
| Game world | **Player character:** | N/A (the hangman is not considered a player character). |
| | **Environment:** | A 2-dimensional graphical scenario with the hangman and the possible letters. |
| Virtual interface | **World interface:** | PC display, showing a two-dimensional view of the virtual environment. |
| | **NF interface:** | The chosen letter and the confidence in the classification result appear in the UI. |
| | **Stimuli generator:** | N/A. |
| | **Mental War [26]** | |
| EEG data collection | **Sensors:** | A single dry electrode, positioned at site Fp1. |
| | **EEG device:** | A NeuroSky MindWave. |
| Control interface | **BCI control:** | Attention level, directly measured using the MindWave's eSense metric. |
| | **N/BCI control:** | N/A. |
| Control mechanics | **BCI:** | The intensity of the attention metric is directly proportional to the force that the character uses to push a rope in a tug-of-war match. |
| | **Non-BCI:** | N/A. |
| Game world | **Player character:** | A human cartoon avatar. |
| | **Environment:** | A 2-dimensional graphical scenario that changes according to the game's difficulty. |
| Virtual interface | **World interface:** | A PC monitor display, showing a two-dimensional view of the world and a third-person view of the player character. |
| | **NF interface:** | A vertical bar embedded in the game UI, showing the player's current attention level. |
| | **Stimuli generator:** | N/A. |

**Table 3.** Demonstration of the model and its components (continuation).

| | | |
|---|---|---|
| **MindBalance [14]** | | |
| EEG data collection | **Sensors:** | Two silver chloride scalp electrodes, placed at positions O1 and O2. |
| | **EEG device:** | Biopac biopotential amplifiers. |
| Control interface | **BCI control:** | SSVEP, using two PSD estimation methods: squared 4-second FFT, and FFT of autocorrelation. |
| | **N/BCI control:** | N/A. |
| Control mechanics | **BCI:** | The SSVEP command is used to choose the direction of the character movement (left or right) to regain balance in a tightrope. |
| | **Non-BCI:** | N/A. |
| Game world | **Player character:** | A three-dimensional humanoid-like creature. |
| | **Environment:** | A virtual, three-dimensional scenario with a platform and a tightrope. |
| Virtual interface | **World interface:** | PC monitor display, with a 3D view of the environment and a third-person view of the character facing the camera. |
| | **NF interface:** | The character animation serves as feedback of the selected movement direction. Auditive feedback is also provided. |
| | **Stimuli generator:** | Embedded in the game screen. Two squares with checkerboard patterns flashing at two different frequencies (17Hz and 20Hz) to elicit SSVEP responses. |
| **MindGame [5]** | | |
| EEG data collection | **Sensors:** | 10 electrodes placed over the parietal and occipital regions. |
| | **EEG device:** | A Mindset24 EEG amplifier. |
| Control interface | **BCI control:** | P300, using PCA as method for feature extraction and FLDA as classifier. |
| | **N/BCI control:** | N/A. |
| Control mechanics | **BCI:** | Used to select a target tree in the game world. The player must reach all trees to win the game. |
| | **Non-BCI:** | N/A. |
| Game world | **Player character:** | A two-dimensional cat avatar. |
| | **Environment:** | A virtual, 3D room with a checkerboard-styled floor and 2-dimensional trees. |
| Virtual interface | **World interface:** | A display, showing the whole scenario and a third-person view of the character. |
| | **NF interface:** | The direction and number of steps of the character's movement serves as feedback for the selected target. |
| | **Stimuli generator:** | Each target tree in the game world also serves as stimulus, flashing consecutively. |
| **Mind the Sheep! [23]** | | |
| EEG data collection | **Sensors:** | Five electrodes, positioned at sites PO3, O1, Oz, O2 and PO4. |
| | **EEG device:** | A Biosemi ActiveTwo system. |
| Control interface | **BCI control:** | SSVEP, using a canonical correlation analysis algorithm. |
| | **N/BCI control:** | Mouse. |
| Control mechanics | **BCI:** | Used to select a target dog in the game world. |
| | **Non-BCI:** | Used to point to the location to which the selected dog must move. |
| Game world | **Player character:** | Several dogs from the game world serve as player-controllable characters. |
| | **Environment:** | A virtual playground representing a meadow, with obstacles and fences. |
| Virtual interface | **World interface:** | A PC LCD monitor screen, with a top-down view of the game world. |
| | **NF interface:** | A circle around the selected dog serves as feedback for the classification result. |
| | **Stimuli generator:** | Each of the three possible target dog flashes simultaneously at 7.5, 10 and 12 Hz. |
| **Pinball [25]** | | |
| EEG data collection | **Sensors:** | 64 sensors (implied by the number of channels). |
| | **EEG device:** | Not informed. |
| Control interface | **BCI control:** | Motor imagery, with CSP filters to extract power features to a LDA classifier. |
| | **N/BCI control:** | A lever. |
| Control mechanics | **BCI:** | A low-level command is used to control the left and right paddles of a pinball machine, using the respective imagined movement (left hand, right hand). |
| | **Non-BCI:** | The player must pull the lever to launch a new ball. |
| Game world | **Player character:** | N/A. |
| | **Environment:** | A physical pinball machine. |
| Virtual interface | **World interface:** | The machine itself serves as a physical, auditory and visual interface. |
| | **NF interface:** | The movement of the paddles serve as feedback for the classified command. |
| | **Stimuli generator:** | N/A. |
| **Space Connection [22]** | | |
| EEG data collection | **Sensors:** | A single dry electrode, positioned at site Fp1. |
| | **EEG device:** | A NeuroSky MindWave. |
| Control interface | **BCI control:** | The player's level of attention, measured using the NeuroSky's eSense metric. |
| | **N/BCI control:** | Mouse, keyboard and relaxation level (measured through respiration rate). |
| Control mechanics | **BCI:** | With the attention level above a certain threshold, the player can move objects. |
| | **Non-BCI:** | Targeting and movement (Mouse and keyboard); and an ability to freeze time (relaxation level). |
| Game world | **Player character:** | Two virtual, 3-dimensional human characters. |
| | **Environment:** | A virtual, 3-dimensional spaceship, containing multiple levels with puzzles. |
| Virtual interface | **World interface:** | A PC monitor display, showing a first-person view of the player's character. |
| | **NF interface:** | Power bars in the game UI indicate the attention (and relaxation) levels. |
| | **Stimuli generator:** | N/A. |
| **Thinking Penguin [16]** | | |
| EEG data collection | **Sensors:** | A cap with five electrodes, placed at position Cz and four orthogonal sites. |
| | **EEG device:** | A 16-channel g.Tec biosignal amplifier. |
| Control interface | **BCI control:** | Motor imagery, detected using a LDA classifier for ERS and ERD frequency bands. |
| | **N/BCI control:** | A joystick (and a push-button in non-BCI gameplay). |
| Control mechanics | **BCI:** | Used to make the character jump to catch fish. |
| | **Non-BCI:** | Controls the left-right movement of the character. |
| Game world | **Player character:** | A three-dimensional penguin avatar. |
| | **Environment:** | A virtual, three-dimensional snowy mountain. |
| Virtual interface | **World interface:** | A 3D virtual reality environment, projected in the walls of a four-sided room. |
| | **NF interface:** | The jumping of the penguin serves as feedback for the detection of the desired motor imagery. |
| | **Stimuli generator:** | N/A. |
| **VR Maze [10]** | | |
| EEG data collection | **Sensors:** | Eight electrodes, positioned at the occipital-parietal region. |
| | **EEG device:** | A g.Tec g.MOBIlab+ device. |
| Control interface | **BCI control:** | SSVEP, detected using a canonical correlation analysis algorithm. |
| | **N/BCI control:** | N/A. |
| Control mechanics | **BCI:** | Used to select a target tile destination for the player to move. |
| | **Non-BCI:** | N/A. |
| Game world | **Player character:** | A sphere. |
| | **Environment:** | A virtual, three-dimensional grid, with objects or empty spaces in each tile. |
| Virtual interface | **World interface:** | A monitor or an Oculus Rift head-mounted virtual reality device. |
| | **NF interface:** | The movement of the sphere in the grid serves as feedback for the selected tile. |
| | **Stimuli generator:** | Each tile perpendicular to the sphere flashes at a different frequency as stimulus. |

details about the game architecture (e.g., local or networked) or the game genre, which can be described implicitly through the appropriate components.

In the same sense, the values obtained from the demonstration show that it is possible to group common classified values, e.g., the employed EEG device or the virtual interface, which seem to have a limited number of possible values—at least for atomic information, such as whether the interface is virtual or physical; auditive, somatosensory or graphical; and its dimensions. This could allow not only for a pre-defined list of classification values for such specific components, but also to a classification scheme based on these values, i.e., possibly a new taxonomy constructed upon the proposed model. This new taxonomy could separate these classification values in a more direct fashion, as opposed to the descriptive nature of the model's components, allowing for a more direct comparison of games from the literature. However, as games are fundamentally different from one another, open descriptions are still required to fully describe the concept of the game.

Lastly, it is also important to notice that the proposed model, although is not directly a system architecture framework, can be used as a base for the development of new EEG-controlled games and the construction of their software architecture, as its components and their connections are an abstraction and can be instantiated in numerous ways, using any supported and available technology. A similar approach has been employed, for example, by Sung et al. [24], in which the authors built a framework for EEG-based serious games based on their proposed model.

### 5.1 Limitations

The demonstration of the model also showed some of its limitations. As aforementioned, the first limitation is related to the extension of the described data, which allows for a general overview of the game and how it is played with the BCI controls, but may lack some details about the employed signal processing algorithm and the game, such as its platform and number of players, which have no specific component to represent them and must be implied through the description of related components. The player(s) from Fig. 6, for example, could be a component itself, representing the number of players and the target audience for the game. Although interesting, this approach was not employed in the current model as it is intended to represent EEG-controlled games, and the player is technically not a part of the game itself. However, although the model could be expanded to represent such details more precisely, it remains an open discussion whether the player should be considered a component of the model or an element that participates in its function.

Another limitation is related to the independence of each component in relation to each other. Some components appear to provide less contribution to the general understanding of the game without the complement of other components; for example, the *Player Character* component provides a very specific information that, although generally necessary for the context of the *Control Mechanics* and the *Virtual Interface*, could be implicitly represented through

other components. Merging these information into other general components could, however, increase the difficulty in extracting specific data from each game in order to compare them (or to describe the concept of a new game), as too much information would be gathered into a single component.

## 6 Conclusion

This work presents a generalized model for EEG-based BCI-controlled games. The model is intended to represent such games by describing their functional and abstract components and how they are connected to each other. To demonstrate its usefulness and representativeness, a set of EEG-based BCI games from the literature was described using the components from the model. The demonstration showed that the model is capable of representing aspects both from the classic EEG signal processing steps based on neurofeedback applications, and from the game itself, providing an overview of the game, how the player interacts with it and how it is played using both the BCI and non-BCI controls.

The principles that guided the construction of the model allow for its adaptation to different contexts and applications, and for it to evolve and expand with new components depending on the needs of the researcher. It is expected that, as the model evolves, it will be able to represent not only EEG-controlled games, but also studies involving those games and the contexts in which they are being applied, facilitating its employment in the comparison of different BCI-based studies—e.g., in meta-analyses for comparing the performance of different signal processing algorithms for the classification of EEG signals, or the effects of playing EEG-based serious games in subjects for clinical trials.

The proposed model can also help researchers in the design and development of new EEG-controlled games, and guide future studies that employ those games. Future works, in this sense, involve using the model as a base for the design and development of new EEG-controlled games, as well as conducting and comparing primary studies involving those games. In addition, a model-based taxonomy that groups the possible instantiations of each component hierarchically could also be developed based on the presented demonstration.

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