# Model, Taxonomy and Methodology for Research Employing EEG-based BCI Games

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***Abstract.*** *The thesis summarized in this work presents a model for representing EEG-based BCI games, a taxonomy for classifying and comparing studies of the field, and a methodology for conducting scientific studies using those games. The model is intended to describe and develop new EEG games by instantiating its components. The CoDIS taxonomy considers four aspects of such games: concept, design, implementation and study, each with different dimensions to represent various of their characteristics. Based on the model and the taxonomy, the PIERSE methodology was developed for the planning, implementation, execution and reporting of scientific experiments using those games. The contributions of the thesis are detailed in various dimensions in this manuscript.*

## 1. Introduction

Brain-Computer Interfaces (BCI) research went through a massive growth in the last few decades. Conceived initially as an alternative treatment option for restoring communication and motor movement in physically-impairing conditions, systems based on direct neural control, especially those controlled by non-invasive modalities such as electroencephalography (EEG), are also starting to find applications in domestic environments, entertainment and gaming. Games based on EEG are being increasingly developed and applied in both clinical and domestic 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.

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. These games have the potential to be employed in many different applications, such as being a treatment option to help patients in rehabilitation and training cognitive functions through neurofeedback. 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, benefiting both healthy and impaired players. This topic is being investigated not only in the scope of the academia, but by technology companies as well, such as Microsoft and IBM.

The development of BCI games raises challenges that are related to BCI and games. From the perspective of BCI, it must be ensured that the system is precise enough to 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 desires 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 BCI and Games.

Despite these recent advancements, there is still a lack of a common theoretical foundation for the development of EEG-based BCI games and for studies that employ them, including specialized representational schemes, terminology, and an overlap of methods from different fields. The thesis summarized in this work, developed between 2017 and 2022 despite the difficulties of performing a doctorate during a pandemics such as the COVID-19, aims at helping closing this gap by showing that an EEG-based BCI game can be defined using a general model that represents the functional and conceptual components of a BCI system and a game simultaneously; that the terminology of both fields can be unified into a single taxonomic scheme based on this model; and that both the model and the taxonomy can serve as a theoretical framework for a methodology that guides the process of planning, conducting and reporting studies in the field.

### 1.1. Context and motivation

The motivation of this research arose from the investigation of the field of BCI, focusing on its practical applications. The foundation on which it stands was constructed based on our research on the area, i.e., a systematic literature review of BCI games based on consumer-grade EEG devices; the development of two EEG-based games, being one based on single/multiplayer attention control and the other based on meditation control; and experiments using those games to investigate the influence of visual and auditory stimuli on subjects' attention and meditation, respectively. Each of these studies, most of them refined and published in the first half of the doctorate program, served as base for the development of the thesis. They were the result of our continuous investigation of innovative interaction, starting on my undergraduate course on Computer Science, in which we researched the application of such interfaces on games, that is, the use of gestural interaction in a game of chess [Vasiljevic et al. 2014] in comparison to traditional controls. These researches were the basis for my undergraduate thesis and resulted in a deeper analysis of BCI in my graduate programs, i.e., the investigation of BCI-based games using consumer-grade EEG devices, which started during my masters and were refined during my doctoral program, and the theoretical and methodological artifacts produced afterwards.

### 1.2. Goals and research methodology

The main objective of this research is to develop a new theoretical framework for representing and developing studies involving EEG-based BCI systems in the context of games. This main objective can be divided into the following specific goals:

- To survey and review the field of EEG-controlled BCI games with both consumer and non consumer-grade devices;
- To elaborate a new model for representing those games;
- To create a model-based taxonomy for the classification of EEG-controlled games and studies using those games; and
- To develop a methodology for performing studies of EEG-controlled games.

Most of this work is a secondary research, meaning that it develops new knowledge based on primary researches (e.g., case studies and experiments). The works presented in the subsequent sections of this article were developed mainly based on past

reviews, other secondary studies and by surveying the literature to gather a deeper comprehension of the field, which allowed the construction of both the model, its extended version, and then the taxonomy for EEG-controlled games and its corresponding evaluation. The development of the methodology was based both on the new model and taxonomy, and on the principles of empirical research for primary studies and hypothesis testing, such as quantitative methods for analysis of statistical significance.

## 2. Background

Brain-Computer Interfaces (BCI) are a novel kind of user interface that relies on measuring the user's brain activity as a mean of controlling an external device. Electroencephalography (EEG) is a neuroimaging modality based on the reading of electrical activity occurring in the brain. This oscillatory electrical activity, also known as brain waves, is generated through the electrochemical interaction of neurons in the synapses, which are propagated from the cerebral cortex (the surface of the brain) to the scalp, i.e., the region of the head bordered by the face and the neck. EEG readings from the scalp offers virtually no risks for the subject nor require surgery for its use. Electrodes are placed on the scalp of the subject and connected to an amplifier, which will then send the amplified signals for filtering and processing as needed. The corresponding BCI system then translates the processed signals into control commands for the target application.

Most BCI systems work by self-regulation, i.e., the users intentionally regulates their brain activity to perform an action within the system. This process is performed by providing the users with a feedback about their current brain activity, called neurofeedback, which they can use to try to generate a specific pattern of brain waves. The cyclical process of reading brain waves, performing actions and providing feedback is called "closed-loop neurofeedback". Specific features are analysed and extracted from the brain waves, and translation algorithm (e.g., classification or regression by machine learning methods) uses these features to generate a control signal, which will be identified by the target application as an input command. The application then may provide feedback about its internal state and neurofeedback about the user's brain activity. A complete background of the field of BCI from the perspectives of Games and Interaction Design is presented in Chapter 2 of the thesis (pages 6 to 40).

## 3. A general model

Our systematic review on BCI games based on consumer-grade EEG devices, which analysed 82 games filtered from 829 literature works, and later a more general literature survey on endogenous and exogenous BCI control signals that focused on over 600 studies of the field, revealed theoretical and methodological gaps in the field of EEG-based BCI games, which we began to close by building an unified functional and structured model for such systems. This systematic literature review is published in a journal [Vasiljevic & Miranda 2020a], while the initial version of the general model is published as a full paper in the proceedings of a conference [Vasiljevic & Miranda 2020b]. The more general survey is being prepared and revised as an article to be submitted in a relevant journal of the field.

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 was no model for representing EEG-controlled games and the specific components, attributes and features that constitute them before the development of this thesis. In this sense, the main objective of Chapter 3 of the thesis 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, and was constructed for representing virtually any kind of game that is controlled in any aspect using EEG. The model itself is based on the closed-loop neurofeedback scheme for BCI-based systems, as described in Section 2. The complete model, its foundation, derivation process, and demonstration of its use is present in Chapter 3 of the thesis (pages 41 to 58).

## 4. The CoDIS taxonomy

The development of the general model for BCI games, including its literature background of over 600 references from surveying the field, and the implementation of two EEG-based games served as a theoretical foundation for developing a classification scheme for such games and studies that employ them. The more technical development of these games directly influenced on most of the construction of this scheme, especially as an initial input and base for its Design and Implementation facets, which were later refined with other games from the literature. This classification scheme is published in a journal [Vasiljevic & Miranda 2023], while the processes of design, implementation and evaluation of these two games are published as full papers in the proceedings of a conference [Vasiljevic et al. 2018a, Vasiljevic et al. 2018b]. A more specific manuscript reporting a formal evaluation of this classification scheme is also being prepared and revised as an article to be considered for publication in a journal.

The proposed taxonomy, called CoDIS, was constructed and refined in an iterative manner. The CoDIS taxonomy is faceted, rather than hierarchical, meaning that there is no implicit relationship between the classification categories, and no category is more important or general than the others, allowing to classify an entity based on multiple dimensions, or characteristics. The taxonomy has four facets, being three related to the BCI game itself and one related to studies using this game. The three facets related to the game are based on the model described in Section 3, considering the game as abstract layers of implementation, design and concept, and an interface for the player to interact with, which is an instantiation of the design. A complete description of each facet, dimension, possible attribute classification, its development process and examples are present in Chapter 4 of the thesis (pages 59 to 100). The complete description of the method, results and discussion of an objective evaluation of the taxonomy are present in Chapter 5 of the thesis (pages 101 to 138).

## 5. The PIERSE methodology

The development of two EEG-based games were followed by three controlled experiments using those games. The first experiment was aimed at investigating the possible influence of graphical elements on players' performance and control, which relied on their attention over time. All subjects participated in six experimental sessions with a total of 240 game matches. The second experiment was aimed at investigating the effects

of auditory stimuli on players' meditation and mental workload. Two groups of subjects (with and without auditory stimuli) participated in three experimental sessions each, totalling 144 game matches. The third experiment was aimed at investigating multiplayer aspects of BCI games, especially game experience and social interaction during gameplay. Subjects were divided in pairs into two groups (competitive and collaborative), for a total of 40 game matches.

The results of these experiments helped in formalizing a methodology for scientific experiments in BCI research. These three scientific experiments are published as journal articles [Vasiljevic & Miranda 2022, Vasiljevic & Miranda 2019a, Vasiljevic & Miranda 2019b][(1)]. A manuscript describing and formalizing this methodology is being prepared to be submitted to a prominent journal of the field. The main objective of the proposed methodology, called PIERSE, is to serve as a set of procedures for the **P**lanning, **I**mplementation, **E**xecuting and **R**eporting of **S**cientific **E**xperiments that employ EEG-based BCI games as a mean of answering a research question. The full and detailed description of the PIERSE methodology, including all steps of each stage, guidelines for its use, demonstration of use case scenarios and objective evaluation are presented in Chapter 6 of the thesis (pages 139 to 215).

## 6. Conclusion

This work presented scientific tools and a methodology for representing, classifying and conducting empirical studies using BCI systems, focused on the application domain of games. The development of these scientific tools and the methodology was aimed at helping closing the gap between the fields of BCI and Games, by providing an unified scheme and terminology for the representation and classification of EEG-based games and studies that employ them, and a systematic sequence of procedures to design, execute and report new studies in the field. The results obtained from this thesis derived several contributions for the field of Games. As mentioned throughout this article, these results have been disseminated through various high-impact and relevant venues.

It is also worth to mention other researches that were performed during the development of the thesis. The PGIRec (Player-Game Interaction Recorder) software was also developed and employed for recording and analysing the empirical experiments that served as base for the PIERSE methodology. The development process and the description of this tool is published as a full paper in SBGames[(2)] [Bento et al. 2022], while an extended version of this work is also being reviewed for publication in a journal after an invitation by the editors.

In summary, in addition to the prizes and the recognition already achieved by some of the work produced from this doctorate thesis, its scientific productions are contributing to the field of Games, with their impact totalling, to this date, 152 citations (total from Google Scholar), 93 from Scopus, and 78 from Web of Science, in addition to over 7,669 views and downloads.

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[(1)] Most Cited Articles of Entertainment Computing (published within the last 3 years) in 2021.

[(2)] Best Paper Award of SBGames'22.

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