Model, Taxonomy and Methodology for Research Employing Electroencephalography-based Brain-Computer Interface 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[(1)] and IBM[(2)].

[(1)] microsoft.com/en-us/research/project/brain-computer-interfaces/.

[(2)] research.ibm.com/publications/a-robust-low-cost-eeg-motor-imagery-based-brain-computer-interface/.

The development of BCI games raises challenges that are related to BCI and games. 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 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, especially Human-Computer Interaction (HCI), Games, Physiological Computing (PC), Artificial Intelligence (AI), and Machine Learning (ML).

Despite these recent advancements and challenges, 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 (e.g., tangible user interface [Vasiljevic et al. 2012]), starting on my undergraduate course on Computer Science[(3)], in which we researched the application of such interfaces on games (e.g., the use of gestural interaction in a game of chess [Vasiljevic et al. 2014] in comparison to traditional controls [Vasiljevic et al. 2016]). These researches were the basis for my undergraduate thesis and resulted in a deeper analysis of brain-computer interfaces 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.

Performing a literature review has revealed that, although there are models for describing games, BCI-based systems and studies involving those systems, there was no model or conceptual scheme for representing and organizing games controlled by EEG

[(3)]Graduated with honors, being awarded a medal for academic merit.

by common characteristics, which current models could not represent completely without loss of information. This is due, among other factors, to the field being relatively new and, as aforementioned, the overlapping of many different areas with different backgrounds and terminologies, which can cause confusion for developers and researchers of Computing and, especially, of HCI and Games.

These issues motivated the development of a new theoretical framework for describing EEG-controlled BCI games in a more general manner, which consists of a model and a taxonomy that joins concepts of both the fields of BCI and games, and which may serve as a base for conducting reviews and meta-analyses in both areas using their components and dimensions. These representation schemes also served as a base for the development of a new methodology for performing primary studies involving EEG-controlled games.

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 in the field 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 a process known as self-regulation, i.e., the users intentionally regulates their brain activity to perform an action within the system. This process of self-regulation 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". In this scheme, the EEG signal is acquired from the subjects' brain, and specific features are analysed and extracted from this signal. A 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.

Control signals are commands sent from the stage of signal translation to the target application. Endogenous control signals are those generated independently and regardless of external stimuli, i.e., the user is responsible for eliciting them without aid from the system or from peripheral devices. Examples of endogenous control signals employed currently in BCI research are motor imagery, measurements of cognitive states and identification of emotional states. In contrast with endogenous control signals, exogenous signals are those elicited through any kind of stimulus external to the user. Popular exogenous control signals in EEG-based BCI systems are the visual P300 and the SSVEP (Steady-State Visually Evoked Potentials). A complete background and review of the field of BCI from the perspectives of Interaction Design, Games and Machine Learning 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, which 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 a functional model for such systems. This systematic literature review is published in the International Journal on Human-Computer Interaction [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. The model was constructed for representing virtually any kind of game that is controlled in any aspect using EEG. The main principles that guided the construction of the model were that: the BCI system and

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

The model itself is based on the classical closed-loop neurofeedback scheme for BCI-based systems, as described in Section 2. 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 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 the International Journal on Human-Computer Interaction [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.

Previous studies presented models and taxonomies for BCI systems and for games to standardize the knowledge of these fields in functional and conceptual manners, but there was no taxonomic scheme for representing games using EEG as a control input before the development of this thesis. In this context, Chapter 4 of the thesis describes a taxonomy for EEG-controlled games. A taxonomic scheme for a given field can contribute as a framework for performing systematic literature reviews and meta-analysis, as well as serving to standardize the terminology of the area, especially given the multidisciplinary aspect of brain-computer interfaces. For the specific case of BCI, a taxonomy could help in the design of new EEG-controlled games, to find and employ existing games, and, as a consequence, discovering gaps and research opportunities, as it can be used to classify and group those existing games and the studies that employed them based on common characteristics. The proposed taxonomy, called CoDIS, was constructed and refined in an iterative manner. Its foundation is based on an extended version of our general model for EEG-controlled games, which was constructed for representing virtually any kind of game that is controlled using EEG.

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. Instead, the investigated phenomenon is seen with multiple facets, 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. The first three facets are named after the three corresponding abstract layers, i.e., **Co**ncept, **D**esign and **I**mplementation facets, and each individual facet is independent from one another. The fourth one is the **S**tudy facet, which is used to represent studies that employ an implementation.

The dimensions and attributes of the proposed taxonomy were defined through careful inspection of games and studies from the literature, observing common and recurring data that were employed to describe the game and the BCI system. 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 proposed taxonomy and each of its dimensions were also evaluated to verify whether they are adequate to sufficiently represent EEG-based BCI games and studies that employ them. The taxonomy was evaluated using three metrics defined to represent its appropriateness, easiness and completeness, and based on a representative set of literature works as source for the classification procedure. The results of the evaluation process show that most attributes were appropriate for representing the literature of EEG-based BCI games, although no study provided enough information for classifying all attributes at the same time. The complete description of the method, results and discussion of this evaluation are present in Chapter 5 of the thesis (pages 101 to 138).

5. The PIERSE methodology

In the previous sections, we have presented a general model for representing EEG-based BCI games and a taxonomy for classifying BCI games and studies that employ those games in empirical research. 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 mainly on their attention over time. All subjects participated in the course of 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 PGIRec software was also developed and employed for recording and analysing over 17 hours of these empirical experiments. The development process and the description of this tool is published as a full paper in a conference[(4)] [Bento et al. 2022], while an extended version of this work is

[(4)] Best Paper Award.

also being reviewed for publication in a journal after an invitation by the editors.

The results of these experiments influenced on the development of the model and consequently on the CoDIS taxonomy, but more importantly, helped in formalizing a methodology for scientific experiments in BCI research. These three scientific experiments are published as journal articles in Behaviour & Information Technology [Vasiljevic & Miranda 2022], Interacting with Computers [Vasiljevic & Miranda 2019a], and Entertainment Computing[5] [Vasiljevic & Miranda 2019b]. A manuscript describing and formalizing this methodology is being prepared to be submitted to a prominent journal of the field.

Although the model provides a base for describing existing BCI games and supports the development of new ones, and the taxonomy facilitates the comparison and analysis of literature studies from the field, neither can guide, by themselves, the conduction of new empirical studies that uses BCI-based games in their experimental task. In addition, the evaluation of this taxonomy showed that many important attributes that could indicate the internal and external validity of the results are not always considered when reporting these studies. The aim of Chapter 6, therefore, is to present a methodology that may serve as a general and standardized foundation for the development and reporting of new studies in the field of BCI using games, especially in researches that involve investigating the user experience; the effects of the interaction on the subjects; and the performance of the BCI system.

A methodology is a systematic sequence of processes to solve a problem or to reach a given goal. Although there are general guidelines for BCI experiments and frameworks for specific cases of BCI research and game development, there was, to our knowledge, no formal methodology to guide primary studies using BCI-based games from their conception to their execution and reporting before the development of this thesis. In this sense, 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 methodology is divided into four major stages, and each stage produces an output that serves as base for the next one. 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 resulted in several contributions and scientific productions for the field of Computing, including the areas of

[5]Most Cited Articles (published within the last 3 years, i.e., since 2018) in 2021.

Human-Computer Interaction, Games, Physiological Computing, Artificial Intelligence, and Machine Learning.

The model for EEG-based BCI games was the first major contribution of this thesis. The development of the model was the initial step in unifying concepts of both fields of BCI and Games, since past existing models and representation schemes could not fully represent those systems without loss of information. The model can be employed not only for representing existing game systems, but its components can also be instantiated as an initial architecture for the development of new BCI systems. Its construction and derivation process from the classical closed-loop neurofeedback scheme could also serve as base for generalizing the model for other applications, since the data collection, pre-processing, processing and feedback components of the closed-loop architecture are equivalent to those of systems from related contexts.

The CoDIS taxonomy, based on the model, is also one of the major contributions of this thesis. It expands the representativeness of the model to also include any studies that employ EEG-based BCI games, allowing those studies to be classified in relation to several dimensions according to the goals of the researchers. The taxonomy allows not only to classify primary studies in a systematic manner, but also to group and compare different studies in relation to common attributes, which is especially important in the context of surveys, systematic reviews and meta-analyses. The validation of the CoDIS taxonomy was also particularly important, since the method that was developed and employed for this validation, which is a combination of different methods employed in various areas of research to evaluate taxonomies and ontologies, may also be applied with other classification schemes.

The PIERSE methodology aggregates the results of the model, the taxonomy and its corresponding validation as its foundation. In addition to providing a systematic and sequential set of procedures for developing new primary studies in the field, the description of each stage of the methodology also provides general guidelines for its use and the theoretical knowledge that guided its construction. It can be employed not only through the stages of conceptualizing a new study starting from a problem description and progressively reaching its reporting, but also to complement ongoing researches and to analyse existing studies from the field in relation to the information that they provide in their reports. The guidelines for these stages, in addition to methods for the planning, execution and reporting of scientific studies in the field, also describe techniques for the interaction design, architecture and development of new EEG-based systems using either endogenous or exogenous control signals, or the adaptation of non-BCI systems to employ EEG-based controls.

It is also worth to mention other researches that were performed during the development of the thesis. Although not directly related to the work performed in the thesis, a data science and bibliometric analysis of conferences from the field of HCI was also performed as a collaboration with another graduate student in the context of other works from our Research Group that were being performed during my doctorate program, published as a conference full paper [Lima et al. 2019] and later in the Journal on Interactive Systems [(6)] [Lima et al. 2021] as an extension as response of an invitation by the editors.

[(6)] Most Read Papers in 2021.

6.1. Scientific publications, relevance and impact

As mentioned throughout this article, our research results have been disseminated through various high-impact and relevant venues. With the works directly related to the development of the thesis, we advanced on the state of the art and technique of Computing by helping at closing the gap between the fields of BCI and Games, with both theoretical and practical results and a new methodology for future studies in the area. These contributions are specially relevant to the fields of HCI, Games, PC, AI, and ML.

In addition to the direct contributions to these fields, described in details in each corresponding chapter, it is also worth mentioning the impact of the thesis for related studies in Computing and correlated areas. To measure this impact, the scientific productions that were developed and published during my doctorate program can be analysed for their influence on other relevant works. Our most influential studies have been cited and used as methodological reference, for example, by researchers from universities around the world in studies published in important journals and conferences of the fields of Human-Computer Interaction, e.g., ACM Conference on Human Factors in Computing Systems (CHI), Symposium on Computer-Human Interaction in Play (CHI-PLAY), International Journal on Human-Computer Studies (IJHCS), International Journal on Human-Computer Interaction (IJHCI), and International Journal on Child-Computer Interaction (IJCCI); and Games, e.g., IEEE Transactions on Games, Entertainment Computing, and JMIR Serious Games.

Not limited to the fields of HCI and Games, researchers from other fields are also using the results of our work, such as Computing in general, e.g., ACM Computing Surveys (CSUR) and Sensors; Neuroscience and Psychology, e.g., Frontiers in Neuroscience and Frontiers in Psychology; Engineering, e.g., IEEE Sensors; and the specialized field of BCI, e.g., the journal of Brain-Computer Interfaces. Going beyond results derived from the academia, this work is also being employed as reference for other areas with practical applications in Society, such as government research[7] and companies[8].

In summary, in addition to the prizes and the recognition already achieved by some of the work produced from this doctorate thesis in Computing, its scientific productions are contributing to the field and correlated areas, 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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