



FEDERAL UNIVERSITY OF RIO GRANDE DO NORTE
CENTER OF EXACT AND EARTH SCIENCES
DEPARTMENT OF INFORMATICS AND APPLIED MATHEMATICS
GRADUATE PROGRAM IN SYSTEMS AND COMPUTING
MASTER'S DEGREE IN SYSTEMS AND COMPUTING



Brain-Computer Interface Games based on Consumer-Grade Electroencephalography Devices: Systematic Review and Controlled Experiments

Gabriel Alves Vasiljevic Mendes

Natal-RN

July 2017

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**Brain-Computer Interface Games based on
Consumer-Grade Electroencephalography Devices:
Systematic Review and Controlled Experiments**

Master thesis presented to the Graduate Program in Systems and Computing of the Department of Informatics and Applied Mathematics at the Federal University of Rio Grande do Norte as a partial requirement for the degree of Master in Systems and Computing.

Line of research:
Software Engineering

Advisor

Prof. Dr. Leonardo Cunha de Miranda

GRADUATE PROGRAM IN SYSTEMS AND COMPUTING (PPGSC)
DEPARTMENT OF INFORMATICS AND APPLIED MATHEMATICS (DIMAP)
CENTER OF EXACT AND EARTH SCIENCES (CCET)
FEDERAL UNIVERSITY OF RIO GRANDE DO NORTE (UFRN)

Natal-RN

July 2017

Catálogo da Publicação na Fonte. UFRN / SISBI / Biblioteca Setorial
Centro de Ciências Exatas e da Terra – CCET.

Mendes, Gabriel Alves Vasiljevic.

Brain-computer interface games based on consumer-grade
electroencephalography devices: systematic review and controlled experiments /
Gabriel Alves Vasiljevic Mendes. - Natal, 2017.

153f. : il.

Orientador: Leonardo Cunha de Miranda.

Dissertação (Mestrado) – Universidade Federal do Rio Grande do Norte.
Centro de Ciências Exatas e da Terra. Programa de Pós-Graduação em Sistemas e
Computação.

1. Engenharia de software – Dissertação. 2. BCI – Dissertação. 3. HCI –
Dissertação. 4. Games – Dissertação. 5. NeuroSky MindWave – Dissertação. 6.
Emotiv Epoc – Dissertação. I. Miranda, Leonardo Cunha de. II. Título.

RN/UF/BSE-CCET

CDU: 004.41

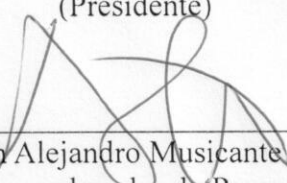
GABRIEL ALVES VASILJEVIC MENDES

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Esta Dissertação foi julgada adequada para a obtenção do título de mestre em Sistemas e Computação e aprovada em sua forma final pelo Programa de Pós-Graduação em Sistemas e Computação do Departamento de Informática e Matemática Aplicada da Universidade Federal do Rio Grande do Norte.



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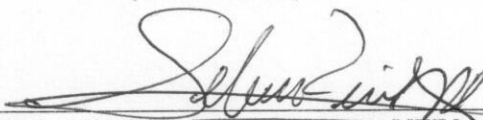


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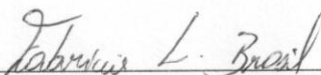
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Julho, 2017

Acknowledgements

I would like to thank my family, specially my parents and siblings, for their endless love and for supporting me in everything that I do and need. Also, to all my friends, who provided support and aid in this important time of my life, and never stopped motivating and believing in me.

To my advisor, Prof. Dr. Leonardo Cunha de Miranda, for motivating me, being comprehensive, patient, and for believing in my potential. Thank you for all the effort, the resources, and the time you have dedicated to me and my work. This research would not be possible without your guidance.

To the Physical Artifacts of Interaction Research Group (PAIRG) and its Laboratory of Physical and Physiological Computing (L2PC), for all the support, resources, and contribution of their members in my work, especially Bruna Camila, for helping with the design and development of the Mental War and Zen Cat games, both of absolute importance in my experiments, and Murilo Bento, for providing important tools to support my experiments, and for his time and dedication in aiding me with my research. Also, Paulo Leonardo, for helping me during the course of my work and providing assistance whenever needed. Thank you all very much.

To my committee members, Prof. Dr. Bruno Motta, Prof. Dr. Selan Rodrigues and Prof. Dr. Fabrício Lima, for accepting to evaluate, guide and contribute to my work.

To the Federal University of Rio Grande do Norte (UFRN), the Department of Informatics and Applied Mathematics (DIMAp), and the National Council for Scientific and Technological Development (CNPq), for providing me with important resources during my research.

To all the subjects who agreed to participate in my experiment in order to help me even at hardship, without asking anything in return, my special thanks. Without you all, this research would not be possible.

“Let the future tell the truth, and evaluate each one according to his work and accomplishments. The present is theirs; the future, for which I have really worked, is mine.”

Nikola Tesla

Brain-Computer Interface Games based on Consumer-Grade Electroencephalography Devices: Systematic Review and Controlled Experiments

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ABSTRACT

Brain-computer interfaces (BCIs) are specialized systems that allow users to control a computer or a machine using their brain waves. BCI systems allow patients with severe physical impairments, such as those suffering from amyotrophic lateral sclerosis, cerebral palsy and locked-in syndrome, to communicate and regain physical movements with the help of specialized equipment. With the development of BCI technology in the second half of the 20th century and the advent of consumer-grade BCI devices in the late 2000s, brain-controlled systems started to find applications not only in the medical field, but also in entertainment. One particular area that is gaining more evidence due to the arrival of consumer-grade devices is the field of computer games, which has become increasingly popular in BCI research as it allows for more user-friendly applications of BCI technology in both healthy and unhealthy users. However, numerous challenges are yet to be overcome in order to advance in this field, as the origins and mechanics of the brain waves and how they are affected by external stimuli are not yet fully understood. In this sense, a systematic literature review of BCI games based on consumer-grade technology was performed with over 2,200 works investigated. Based on its results, two BCI games, one using attention and the other using meditation as control signals, were developed in order to investigate key aspects of player interaction: the influence of graphical elements on attention and control; the influence of auditory stimuli on meditation and work load; and the differences both in performance and multiplayer game experience, all evaluated in the context of neurofeedback-based BCI games in three different controlled experiments, with a total of 40 subjects who played over 420 game matches.

Keywords: BCI, HCI, Games, NeuroSky MindWave, Emotiv Epoc.

Jogos de Interface Cérebro-Computador baseados em Dispositivos Comerciais de Eletroencefalografia: Revisão Sistemática e Experimentos Controlados

Autor: Gabriel Alves Vasiljevic Mendes

Orientador: Prof. Dr. Leonardo Cunha de Miranda

RESUMO

Interfaces Cérebro-Computador (ICCs) são sistemas especializados que permitem que usuários controlem um computador ou uma máquina utilizando suas ondas cerebrais. Sistemas de ICC permitem que pacientes com limitações físicas severas, como os que sofrem de esclerose lateral amiotrófica, paralisia cerebral e síndrome do encarceramento, se comuniquem e recuperem movimentos físicos com a ajuda de equipamentos especializados. Com o desenvolvimento da tecnologia de ICC na segunda metade do século 20 e a chegada de dispositivos comerciais de ICC no final dos anos 2000, sistemas controlados pelo cérebro começaram a ser aplicados não apenas no campo médico, mas também na área de entretenimento. Uma área em particular que está ganhando evidência devido à chegada dos dispositivos comerciais é o campo de jogos de computador, que se tornou popular em pesquisas de ICC por permitir aplicações mais fáceis de usar da tecnologia para ambos usuários saudáveis e não saudáveis. Porém, inúmeros desafios ainda devem ser superados a fim de progredir neste campo, já que ainda não entende-se completamente quais as origens e as mecânicas das ondas cerebrais e como elas reagem a estímulos externos. Neste sentido, uma revisão sistemática da literatura de jogos de ICC baseados em tecnologia comercial foi realizada com mais de 2,200 trabalhos investigados. Baseado em seus resultados, dois jogos de ICC, um utilizando atenção e o outro utilizando meditação como sinais de controle, foram desenvolvidos a fim de investigar aspectos-chave da interação dos jogadores: a influência de elementos gráficos na atenção e no controle; a influência de estímulos auditivos na meditação e na carga de trabalho; e as diferenças no desempenho e na experiência de jogo *multiplayer*, todos avaliados no contexto de jogos de ICC baseados em *neurofeedback* em três diferentes experimentos controlados, com um total de 40 participantes que jogaram mais de 420 partidas dos jogos.

Palavras-chave: BCI, HCI, Jogos, NeuroSky MindWave, Emotiv Epoc.

List of Figures

1	A superior view of a dissection of the cranial meninges	p. 25
2	Frequency bands of EEG signals	p. 26
3	The brain lobes	p. 27
4	BCI consumer-grade EEG devices	p. 31
5	The International 10–20 System	p. 32
6	PRISMA flow diagram.	p. 42
7	Number of games published by year	p. 44
8	Number of games of each genre using each control signal	p. 44
9	Number of games per purpose	p. 46
10	Number of games per platform and per BCI paradigm	p. 47
11	Mental War game matches	p. 68
12	Self-Assessment Manikin	p. 70
13	First experiment protocol	p. 71
14	Average attention of the subjects in each difficulty	p. 73
15	Performance of the subjects in each difficulty	p. 74
16	Average attention of each game mode per session	p. 75
17	Total time spent in each configuration by each subject	p. 76
18	Average Satisfaction, Motivation and Control	p. 77
19	SAM ratings distribution	p. 77
20	Subject using his finger to concentrate	p. 79
21	Zen Cat game match	p. 90
22	Average meditation per session	p. 95

23	Average meditation per session from both groups.	p. 96
24	Boxplots of average meditation per group.	p. 97
25	Boxplot of the self-assessed workload	p. 98
26	Average workload per session	p. 99
27	Boxplots of workload per group	p. 100
28	Mental War multiplayer match.	p. 103
29	Average attention per match of the third experiment	p. 109
30	Average attention per groups of the third experiment	p. 110

List of Tables

1	Search sources.	p. 37
2	Search terms.	p. 37
3	Quality criteria scores.	p. 40
4	Statistics of the games' experiments.	p. 46
5	Procedure for the first experiment	p. 71
6	Statistics of all sessions of the first experiment	p. 73
7	SAM values distribution in each group	p. 77
8	Mauchly's test for sphericity	p. 93
9	Statistics of all sessions of the second experiment	p. 94
10	Statistics of all matches of the second experiment	p. 95
11	Statistics of both groups of the second experiment	p. 96
12	Workload statistics of all sessions.	p. 97
13	Workload statistics of all sessions from both groups	p. 99
14	Statistics of all matches of the third experiment	p. 107
15	Mauchly's test for sphericity (3rd Experiment)	p. 108
16	Statistics of average attention of the third experiment	p. 108
17	Scores of the GEQ core module components	p. 110
18	Average scores of the GEQ social module components	p. 111
19	Scores of the GEQ core module components	p. 111
20	Basic data of the reviewed games.	p. 130
21	Development data from the games.	p. 132
22	Evaluation and experimentation data from the games.	p. 134

23	Attention estimation techniques employed by each game.	p.135
24	Meditation estimation techniques employed by each game.	p.136

List of abbreviations and acronyms

BCI – Brain-Computer Interface

BMI – Brain-Machine Interface

ALS – Amyotrophic Lateral Sclerosis

TUI – Tangible User Interfaces

EEG – Electroencephalography

VEP – Visually-Evoked Potentials

SSVEP – Steady-State Visually-Evoked Potentials

RPG – Role-Playing Game

SLR – Systematic Literature Review

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

GGUI – Game's Graphical User Interface

SAM – Self-Assessment Manikin

AS – Auditory Stimuli

TLX – NASA Task Load Index

GEQ – Game Experience Questionnaire

Table of Contents

1	Introduction	p. 19
1.1	Context and Motivation	p. 20
1.2	Objectives	p. 21
1.3	Research Methodology	p. 22
1.4	Structure	p. 22
2	Background	p. 24
2.1	Brain Waves	p. 25
2.2	BCI Control Signals	p. 27
2.3	BCI Paradigms	p. 29
2.4	BCI Consumer-Grade EEG Devices	p. 30
2.5	Game Platform, Purpose and Genre	p. 32
3	Systematic Literature Review	p. 35
3.1	Methods	p. 36
3.1.1	Eligibility Criteria	p. 36
3.1.2	Information Sources	p. 36
3.1.3	Search	p. 37
3.1.4	Study Selection	p. 38
3.1.5	Data Collection Process and Data Items	p. 40
3.2	Results	p. 41
3.2.1	Study Selection	p. 41

3.2.2	Study Characteristics	p. 43
3.2.3	Additional Analysis	p. 46
3.2.4	Individual Studies	p. 48
3.2.4.1	Attention	p. 48
3.2.4.2	Meditation	p. 51
3.2.4.3	Motor Imagery	p. 52
3.2.4.4	VEP and SSVEP	p. 53
3.2.4.5	Emotion Recognition	p. 54
3.2.4.6	Eye Tracking and Blink Detection	p. 54
3.3	Related Surveys	p. 55
3.4	Discussion	p. 57
3.4.1	Research Questions	p. 57
3.4.1.1	RQ1	p. 58
3.4.1.2	RQ2	p. 59
3.4.1.3	RQ3	p. 59
3.4.1.4	RQ4	p. 60
3.4.2	Related Surveys	p. 62
3.4.3	Complementary Discussion	p. 63
3.4.4	Limitations	p. 64
4	The Influence of Graphical Elements on Users' Attention and Control	p. 66
4.1	Methodology	p. 66
4.1.1	Attention-based BCI game	p. 67
4.1.2	Research Questions	p. 68
4.1.3	Participants	p. 69
4.1.4	Ambient and Materials	p. 69

4.1.5	Procedure	p. 70
4.1.6	Design	p. 71
4.2	Results	p. 72
4.2.1	Does the average level of attention of the subjects changes over time?	p. 72
4.2.2	Does the game's graphical user interface affect the average level of attention of the users?	p. 74
4.2.3	How do the subjects perceive their attention-based control over the game?	p. 76
4.3	Related Works	p. 80
4.4	Discussion	p. 81
4.4.1	Research Questions	p. 81
4.4.2	Related Work	p. 83
4.4.3	Additional Analysis	p. 84
4.4.4	Limitations	p. 86
5	The Influence of Auditory Stimuli on Users' Meditation and Workload:	p. 88
5.1	Methodology	p. 88
5.1.1	Meditation-based BCI game	p. 89
5.1.2	Research Questions	p. 90
5.1.3	Participants	p. 91
5.1.4	Ambient and Materials	p. 91
5.1.5	Procedure	p. 91
5.1.6	Design	p. 92
5.2	Results	p. 92
5.2.1	Does the average level of meditation of the subjects changes over time?	p. 94

5.2.2	Does the game's auditory stimuli affect the average level of meditation of the subjects?	p. 95
5.2.3	Does the subjects' self-assessed workload changes over time? . .	p. 97
5.2.4	Does the game's auditory stimuli affect the self-assessed workload of the subjects?	p. 98
5.3	Limitations	p. 100
6	The Influence of Social Interaction on Users' Performance and Game Experience	p. 102
6.1	Methodology	p. 102
6.1.1	Multiplayer attention-based BCI game	p. 103
6.1.2	Research Questions	p. 104
6.1.3	Participants	p. 104
6.1.4	Ambient and Materials	p. 105
6.1.5	Procedure	p. 105
6.1.6	Design	p. 106
6.2	Results	p. 106
6.2.1	Is there a difference in performance between the collaborative and the competitive groups?	p. 106
6.2.2	Is there a difference in the game experience between the collaborative and the competitive groups?	p. 109
6.3	Limitations	p. 111
7	Final Remarks	p. 113
7.1	Main Contributions	p. 115
7.2	Future Works	p. 115
	References	p. 117
	Appendix A – Additional Data from the Games	p. 129

1 Introduction

A Brain-Computer Interface (BCI) or Brain-Machine Interface (BMI) is a system that allow users to control or interact with computational or mechanical systems without the need of any body movement, using only electrical signals generated in the brain (NICOLAS-ALONSO; GOMEZ-GIL, 2012). This lack of direct physical contact with the system opens the opportunity to physical-impaired users, e.g. ALS (Amyotrophic Lateral Sclerosis) and cerebral palsy patients, to perform everyday activities (WOLPAW et al., 2002), such as walking (for those with impaired limbs), navigating into the Internet, playing games, and communicate (BEVERIDGE et al., 2015).

In the last decade, the research in BCI had a large increase in number and interest (BERGER et al., 2008), especially as a control scheme for video-games (MARSHALL et al., 2013; LOTTE, 2011) as it provides means for any person, including physically impaired patients, to have an entertainment experience without the use of muscles (BEVERIDGE et al., 2015), as the commands are sent directly to the computer from the brain instead of the habitual path of nerves and muscles (LIAROKAPIS; VOURVOPOULOS; ENE, 2014). This increase is also related to the release of consumer-grade devices that make the development of BCI applications easier (AHN et al., 2014), such as the NeuroSky MindWave and the Emotiv Epoc.

These consumer-grade devices open the possibility to the employment of such technology also by healthy users, with emerging applications in entertainment (FOLGIERI et al., 2014; KO et al., 2009; FOLGIERI; ZAMPOLINI, 2015; FOLGIERI; ZICHELLA, 2012), games (LOTTE, 2011; LÉCUYER et al., 2008), education (MOORE, 2003), security (HEMA; PAULRAJ; KAUR, 2008; DAN; XIFENG; QIANGANG, 2012; GUI; JIN; XU, 2014), and communication (BIRBAUMER, 2006; WOLPAW et al., 2002). However, as it is a technology with theoretical background and technical implementation both in its early stages, there are inherent challenges involving the development of such systems, especially with the limitations of the currently available consumer-grade devices. In the case of games, these challenges become more evident as the game flow must keep the player entertained and interested in keep

playing. The temporal resolution of the device or the chosen control signal may disrupt the game flow and cause players to become bored, frustrated and lose interest in the game. Also, games based solely on those measurements may cause the players to feel that they are not in total control of the game, as they would while playing with a standard joystick (HAY, 2013).

Computer games are entertainment programs with a set of rules (gameplay) and a specific goal or win condition (ADAMS, 2010). BCI control can be used not only as a whole new set of interactions with the game without the need of traditional controllers, but also as a complementary input for potentially every game genre, as physiological data such as emotions, attention and stress levels can be applied as modifiers to the gameplay mechanics and change the game environment.

1.1 Context and Motivation

The motivation for this research arose from the investigation of unusual human-computer interfaces. As computational processing power advances, the development of new and more immersible interfaces is possible, e.g. as the touch and voice interfaces replaced the traditional keyboard of smartphones. One of these new interaction paradigms that emerged in the last decades was the Tangible User Interfaces (TUI). Aligned with the proposal of investigating and creating new physical artifacts of interaction, such as the Adjustable Interactive Rings (MIRANDA; HORNUNG; BARANAUSKAS, 2010), the research of unusual interaction paradigms such as TUI and gestural interfaces was pursued, resulting in studies ranging from prototyping of tangible interfaces (VASILJEVIC et al., 2012), domotics (OLIVEIRA et al., 2013), and gestural-based board games (VASILJEVIC; MIRANDA; MIRANDA, 2014, 2016). Based on the proposal of combining unusual interfaces with games, the motivation for the research of BCI-based games arose.

With the development of commercially available, low-cost BCI equipment, especially those based in electroencephalography (EEG) technology, it is now possible that BCI-enabled games become popular and change the way that traditional games interact with its players. These kinds of games can be used not only as entertainment, but with proper training they can also be employed to help increasing the player’s mental functions, such as controlling his/her brain rhythms (PINEDA; ALLISON; VANKOV, 2000), his/her attention (REUDERINK, 2008), or to assist in specific tasks such as teaching and education (e.g. (YILDIRIM; VAROL, 2013)). In addition, such games, which use physiological computing,

are able to recognize and display players' specific emotions and mental states, bringing human-computer interaction closer to human communication (CHANEL; MÜHL, 2015).

However, given the limitations of said technology, there are still numerous challenges to be overcome in order to have reliable systems capable of providing such level of interaction. BCI games tend to be not very appealing to the general public, not only for the need of specific equipment for its function, but also because often they are not very visually attractive, as they are created aiming to conduct scientific research or usually have poor graphics, few or none auditory interface, and simplified gameplay in order to avoid loss of performance and accuracy from the system.

In this perspective, knowing to what extent the visual and auditory stimuli influence on the performance of the players may not only help to further understand how the attention system of the human brain works in parallel with external stimuli, but also give insights to game developers of which limitations they must consider while designing and developing BCI-based neurofeedback games.

1.2 Objectives

Having those issues related to the design, implementation, and both technological and biological limitations of BCI-based games, especially those based on consumer-grade EEG devices, the main objective of this work is to:

- Understand the user interaction of brain-computer interface games based on consumer-grade electroencephalography devices.

Being so, this main objective can be further decomposed into five specific objectives, which are to:

- Perform a systematic literature review in order to identify the developed games in the area, the challenges, and the open topics of the field;
- Design and develop two neurofeedback games, one based on attention and the other on meditation;
- Evaluate and compare the performance and control of players with and without the game's graphical elements;

- Evaluate and compare the performance and workload of players with and without the game’s auditory stimuli;
- Evaluate and compare the performance and game experience of players in collaborative and competitive scenarios.

The second objective is necessary in order to execute the other three, as the games will be used as experimental tools to test the research hypothesis, i.e., whether there is a statistically significant difference in the performance of the players in each case.

1.3 Research Methodology

This research followed an experiment-oriented design and focused on quantitative methods due to its deductive nature. The work itself is a primary research, although a secondary research is presented in Chapter 3. For the most part, quantitative analyses were used, such as statistical tests and performance evaluation. Qualitative analyses were also employed with tools such as questionnaires, interviews, observation and video analysis.

The experiments were planned to use mixed, within-, and between-subjects designs, aiming at answering objective and deductive research questions. The qualitative data was used to corroborate the main findings. For the data collection, it was chosen to collect primary data using the researches’ own software and tools (the developed games and logs) to have more control over the data samples and greater confidence that these collected data match the research objectives.

1.4 Structure

This subsection briefly describes the structure of this master’s dissertation, highlighting the contents of each chapter.

- **Chapter 2 - Background:** This chapter provides a theoretical background of BCI, its technologies, and digital games, which are related to the main concepts of this research;
- **Chapter 3 - Systematic Literature Review:** This chapter presents the systematic literature review of BCI games based on consumer-grade EEG devices, its findings, challenges and open topics of the field;

- **Chapter 4 - The Influence of Graphical Elements on Users' Attention and Control:** This chapter describes the developed attention-based BCI game and the experiment it was employed to. The experiment is related to the first main objective of this work, and its procedures and results are presented and discussed in this chapter;
- **Chapter 5 - The Influence of Auditory Stimuli on Users' Meditation and Workload:** This chapter describes the developed meditation-based BCI game, as well as the procedure and results of the second experiment, related to the second main objective of this work;
- **Chapter 6 - The Influence of Social Interaction on Users' Performance and Game Experience:** This chapter describes the procedure and results of the third experiment, related to the third main objective of this research. Also, the multiplayer version of the developed attention-based BCI game is described;
- **Chapter 7 - Final Remarks:** This chapter concludes this research, describing its results and main contributions.

2 Background

Brain-Computer Interfaces are specialized systems that read, analyze, classify, and interpret specific physiological signals known as brain waves (NICOLAS-ALONSO; GOMEZ-GIL, 2012). The difference between a system that only reads a physiological signal and a BCI is that the later allows the user to interact with a computer or any other machine using this signal, as it provides a communication channel between the user’s brain and a device s/he intends to control (FATOURECHI et al., 2007). The traditional applications for BCI systems mainly focuses on improving interaction experience for disabled people (SEDEEQ; ROMANO, 2014), however, people without any disability are also potential users of solutions which promote interaction between humans and computers through cerebral signals (FERREIRA et al., 2013). The brain waves are the foundation of any BCI system, as every control signal is derived from them.

A BCI system can be classified according to various factors, such as the nature of the device used (invasive or non-invasive), the nature of the signal stimuli (exogenous or endogenous), the nature of the data processing modality (synchronous or asynchronous) (NICOLAS-ALONSO; GOMEZ-GIL, 2012) and how its control signal are applied (active, passive or reactive).

Typically, an EEG (Electroencephalography) approach is used as it is a non-invasive technique, i.e., it does not need a brain implant to collect data from the user. The disadvantage of non-invasive devices is the lower temporal and spatial resolution in comparison to invasive devices. However, it offers no risks to the user, as the device only reads the signals from the scalp (i.e. the area bordered by the face and the neck). Consequently, EEG has been considered the primary choice for developing BCI systems (KIM et al., 2013; MARSHALL et al., 2013). Other modalities besides the EEG include the Magnetoencephalography (MEG), Functional Magnetic Resonance Imaging (fMRI) and Near Infrared Spectroscopy (NIRS).

2.1 Brain Waves

The brain is composed of two types of specialized cells, i.e. neurons and neuroglia. The neuroglia's function is to support the neurons, keeping them in place and providing them with nutrients and oxygen (KANDEL; SCHWARTZ; JESSELL, 2000). The neurons, on the other hand, are responsible for the transmission of information through chemical and electrical impulses, called nerve impulses. This constant flow of electrical current in the brain, caused by the synaptic excitation of the dendrites in the neurons, generates electrical signals that propagate from the encephalic mass to the scalp, which are called brain waves.

Brain waves can be measured in a relatively simple way, using electrodes placed in the scalp. This reading and measuring of brain waves is called electroencephalography, or EEG. EEG is the most used measurement method of brain waves, for its non-invasive (does not requires implants nor surgeries) and simple nature (MARSHALL et al., 2013). However, the captured signals are very weak and of poor quality, as they need to cross several layers of tissues – such as the meninges (i.e. dura mater, arachnoid and pia mater), the skull and the scalp – before being captured by the electrodes. For this reason, it is often necessary to use several electrodes to have a higher spatial resolution and a more precise system. Figure 1 represents the several layers of tissues that the brain wave must travel before being capture by the electrodes in the scalp.

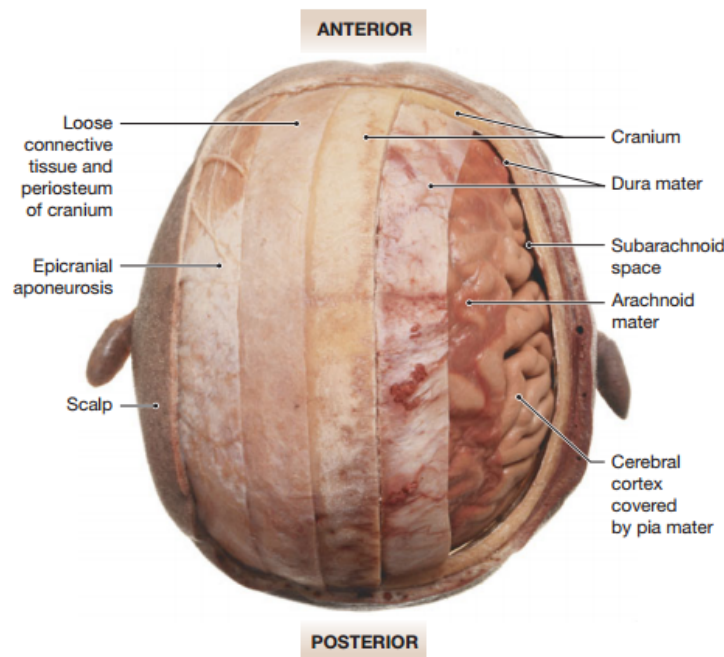


Figure 1: A superior view of a dissection of the cranial meninges. From (MARTINI; TIMMONS; TALLITSCH, 2011)

Brain waves consist of a set of signals that can be divided into five bands, i.e. delta, theta, alpha, beta and gamma waves, classified according to its frequency (Figure 2) (MUNCK et al., 2009). Each band is associated with certain mental states, and the value definition for each band can vary among studies (GERRARD; MALCOLM, 2007). The **delta** waves (below 4 Hz) are low frequency waves associated with deep, dreamless sleep and profound meditation states (NICOLAS-ALONSO; GOMEZ-GIL, 2012). Their amplitude decreases as the baby human ages and are unusual in awoken adult persons, being associated with neurological diseases in such cases (KÜBLER et al., 2001).

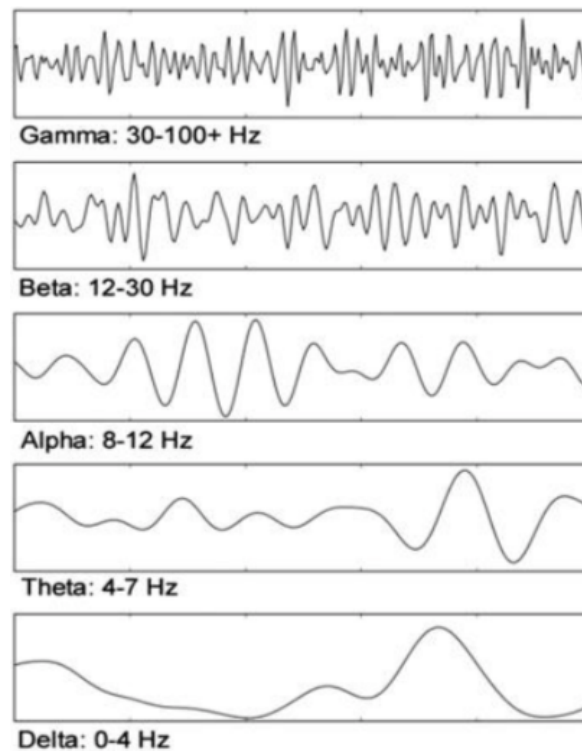


Figure 2: Frequency bands of EEG signals. From [Nowack 1995].

The **theta** waves (from 4 to 7 Hz) are generated during sleep and states of deep meditation. They are usually found in young children and, like delta waves, large amounts during awoken activity in adults are associated with neurological diseases (NICOLAS-ALONSO; GOMEZ-GIL, 2012). The generation of these waves is associated with cognitive processes, learning, memory and dreams. The **alpha** waves (from 8 to 12 Hz) are generated while the brain is in a resting state (VOURVOPOULOS; LIAROKAPIS, 2012). They increase while the eyes are closed and the person is relaxed (PINEDA, 2006), and are found in the occipital and frontal areas, related to visual processing and mental activity, respectively (Figure 3). The alpha waves are suppressed when mental effort is done (BLACK, 1972), allowing this signal to be used to measure to focused mental activity.

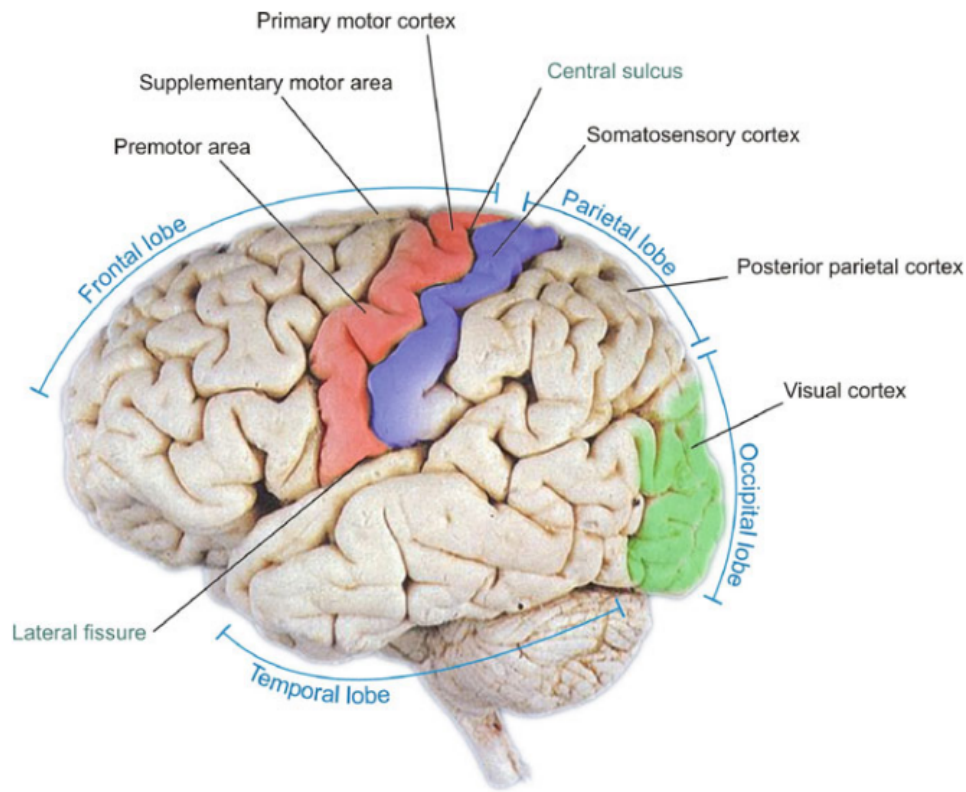


Figure 3: The brain lobes. From (GRAIMANN; ALLISON; PFURTSCHELLER, 2009).

The **beta** waves (from 12 to 30 Hz) are related to motor activities (NICOLAS-ALONSO; GOMEZ-GIL, 2012). They are predominantly found in the frontal and parietal lobes, primarily in the pre-frontal cortex. Beta waves are known to be synchronized and have a symmetrical distribution when there are no motor activities in progress, and become desynchronized and change its symmetry when the sight, the imagination or the performance of a motor activity occurs (PFURTSCHELLER; NEUPER, 2002). They are also related to intense cognitive activity. The **gamma** waves (over 30 Hz) are related to the simultaneous processing of information from various regions of the brain, such as the perception of auditory and visual stimuli, and motor functions.

2.2 BCI Control Signals

Most of the brain signals are still incomprehensible and their origins are unknown. However, some physiological phenomena related to specific brain signals have been decoded and can be used as control signals, as users can learn how to modulate them at will (NICOLAS-ALONSO; GOMEZ-GIL, 2012). Not only specific voltage peaks and event-related signals are possible to be used as control signals, but the classification of the brain state, such as how concentrated the user is or his/her emotions as well.

The theta, alpha and beta waves, for example, are related to certain brain states. Theta and alpha rhythms are stronger and beta waves are weaker when the user is in a **relaxation** or **meditation** state, while beta rhythms are stronger and alpha and theta rhythms are weaker when the user is in a state of **concentration** or **attention**. These changes in the brain waves can be used to measure the user's brain state and are frequently employed as a control signal to BCI systems, as the user can learn to self-regulate his brain state through a process known as neurofeedback (COBEN; EVANS, 2011; MORIYAMA et al., 2012). Various metrics can be used for such measure, such as the beta/alpha and theta/beta ratios (LIU; HOU; SOURINA, 2015; VERNON et al., 2009), the wave's entropy (e.g. sample entropy and fractal dimension) (MING et al., 2009; THOMAS; VINOD; GUAN, 2013a, 2013b) or the wave's raw power spectrum (WANG; LARSEN, 2012).

The sensorimotor rhythms are related to the **motor imagery** (PFURTSCHELLER et al., 2002), and comprise the beta and the mu rhythms (i.e., oscillations in the brain activity in the respective bands). The mu band has the same frequency as the alpha band, but is related to different physiological phenomena, as the amplitude of such rhythms is modulated according to mental tasks related to motor activities without necessarily needing an actual physical movement (LIANG et al., 2014). This amplitude modulation can either be an Event-Related Desynchronization (ERD), which involves the amplitude suppression of the rhythms, or an Event-Related Synchronization (ERS), which involves the enhancement of the rhythms (PFURTSCHELLER, 2001).

Visual stimulations are processed in the visual cortex, located at the occipital lobe. There are specific signal modulations that occur in the visual cortex when certain visual stimuli are perceived, and these modulations, known as **VEP** (Visually-Evoked Potentials), are easily detected, especially as the stimuli moves closer to the visual field, as the VEP amplitude increases. **SSVEP** (Steady-State VEP) is a particular type of VEP that is elicited when the visual stimulus changes at a frequency higher than 6 Hz (BASELER et al., 1994; LIU et al., 2012). This stimulus can be either a pattern or a flashing light or image. In the case of a BCI, a SSVEP can be used as a control signal by means of the eye-gaze, in which the user can select one among many targets by focusing his/her gaze at the corresponding visual stimulus (ZHU et al., 2010).

Emotion is an affective reaction towards an event (MAUSS; ROBINSON, 2009). **Emotion recognition** can be done in a number of ways, either using physiological signals or by self-assessment. Emotion can also be seen as a mental state and, being so, it can be recognized by a BCI system (LI et al., 2009; MURUGAPPAN et al., 2008; LIU; SOURINA;

NGUYEN, 2011). This recognition can be done using artificial intelligence techniques to classify each emotional state according to the EEG data. Also, data from EEG can be combined with other physiological information, such as facial expression and heart rate, for example.

The movement of the eye and the eyelids can be used as a control signal as they generate voltage peaks and fluctuations in the brain waves. The eye blink is usually seen as an artifact, as it may lower the precision of sensors put closer to the eyes, but it is possible to differentiate a spontaneous blink from an intentional one. The eye tracking works in a similar fashion, generating specific voltage peaks in the brain waves that can be captured by the electrodes. Being able to distinguish the top/down, left/right and center gazes of the user allows using the same controls as a motor imagery system would, for example. **Eye tracking** and **blink detection** can also be done using computational vision algorithm and technologies, or by directly reading the cornea-retinal potential in the human-eye; this is known as Electrooculography (EOG) (CHEN et al., 2014).

When attending to an infrequent stimulus among several frequent stimuli, a positive peak in the EEG is elicited. This positive evoked potential occurs after approximately 300ms after the oddball stimulus, and is called **P300** ('P' for "Positive", 300 for 300ms) (KÜBLER et al., 2001; PAVITRAKAR, 2013). This stimulus can be auditory, visual or somatosensory, and the less probable the stimulus, the higher the positive peak. The most widely used application of the P300 evoked potential is the P300 speller, which is composed of a matrix of letters and numbers that randomly flashes at different rates. When the target flashes, the user perceives the oddball stimulus and the P300 is elicited. P300 spellers using auditory cues are also possible (KÄTHNER et al., 2013). This allows to disabled users to write sentences using only his/her sight or auditory sense. However, the information transfer rate and the accuracy of these systems are usually low, and it requires several attempts to select a single character.

2.3 BCI Paradigms

A BCI system can be classified according to the application of the employed control signal. The classifications are "active", "passive" and "reactive" (NICOLAS-ALONSO; GOMEZ-GIL, 2012). An **active BCI** uses an active control mode, i.e., an action is required from the user to activate or modulate the signal. An example of this type of control is the motor imagery, which requires the user to actively imagine an action to perform an action. The **passive**

BCI, on the other hand, does not require a specific action from the user, as the signals are modulated in a passive manner. Examples of this type of BCI are the concentration and meditation levels of the user and his/her emotional state. Those specific signals may also be used in an active manner according to the application, if the user is required to achieve a certain meditation level or a specific emotion, for example.

The third type, **reactive BCI**, requires a reaction from the user, i.e., a stimulus is provided and the reaction from the user to that stimulus is captured. Examples of this type are the SSVEP, which the user must focus his/her gaze in a specific stimulus, and the P300, which the user passively generates a positive voltage peak approximately 300ms after an oddball stimulus. The reactive classification can also be seen as a subgroup of the other two, as in some cases the user must "actively" (e.g., in the SSVEP control signal) or "passively" (e.g., in the P300 control signal) produce the modulation. For the sake of simplicity, the games analyzed in this work will be classified only as passive and/or active, depending on how the user is required to generate the modulation and control the game.

2.4 BCI Consumer-Grade EEG Devices

BCI systems were primarily intended for medical purposes, as it allows patients who suffer from any physical impairment to be able, for example, to move his/her limbs using an exoskeleton (CARMENA et al., 2003; LEBEDEV; NICOLELIS, 2017) or to communicate through his/her brain waves alone (KÜBLER et al., 2001; WOLPAW et al., 2002; BIRBAUMER, 2006). The commercial EEG headsets emerged in the late 2000's and became popular as equipment for acquisition and processing of brain waves in scientific research and game development. The advantage of such EEG devices in relation to medical equipment is their low-cost, ease of acquisition and the abstraction they provide for the development of applications and games, as several layers of the BCI system architecture may be abstracted. Moreover, their wireless capabilities also allows for more comfort for the user, in comparison to the traditional wired electrode caps.

In this study, the following consumer-grade EEG devices were employed in the selected works: the NeuroSky devices, such as the (i) NeuroSky MindSet (Figure 4a), which had its first prototype released in 2007, and the (ii) NeuroSky MindWave (Figure 4b), released in 2011, and the the Emotiv device, i.e. the (iii) Emotiv Epoc (Figure 4c), released in 2009. The NeuroSky and Emotiv headsets are also the most popular consumer-grade EEG devices, according to Chuang and Lee (2012).

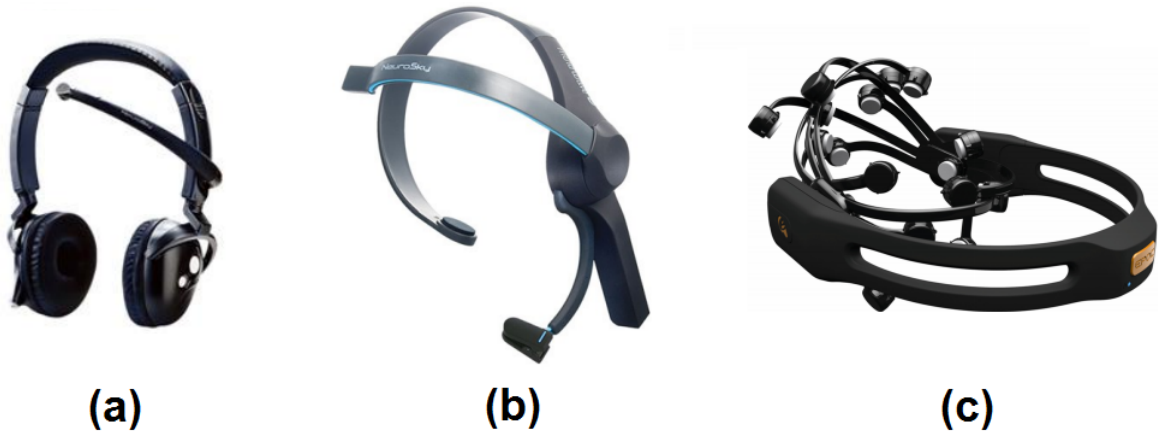


Figure 4: BCI consumer-grade EEG devices: (a) NeuroSky MindSet, (b) NeuroSky MindWave, and (c) Emotiv Epoc. From: (VOURVOPOULOS; LIAROKAPIS, 2012), (HEIDRICH et al., 2015), and (CHARISIS et al., 2015), respectively.

The **NeuroSky headsets**¹ are relatively simple and developed to a more general public. They are available both to PC and mobile devices, have only one sensor that is positioned in the forehead, and use a specific technology called ThinkGear, which processes certain kinds of metrics related to the attention and meditation of the user, called eSenses. These headsets are also capable of identify the blink of the user's eye. The company provides various applications to be used with their devices, such as games and training programs, both paid and free in an online store.

The **Emotiv Epoc**² is a more complex headset, with 14 sensors. As its name suggests, in addition to the basic brain wave data that the device can capture, the Epoc also has a set of softwares able to detect certain kinds of human emotions, such as sadness, anger and happiness, and facial expressions. The headset also has a gyroscope, which provides the relative position of the user's head and to which direction s/he is facing.

Another consumer-grade device was also employed in the work of Lim et al. (2012) and Lee et al. (2013). It is a customized version manufactured by NeuroSky, using two dry sensors placed in the forehead. As there is no model name associated with this headband device, it will be mentioned as "Other device" in this study.

The positions of the devices' sensors are not randomly chosen; they follow the International 10-20 System (SHARBROUGH et al., 1991; NIEDERMEYER; SILVA, 2005), which defines standard electrode placement positions based on two reference points, i.e. the nasion, located at the top of the nose, and the inion, located at the back of the skull (NICOLAS-ALONSO; GOMEZ-GIL, 2012). This scheme is presented in Figure 5.

¹<http://neurosky.com>

²<http://emotiv.com>

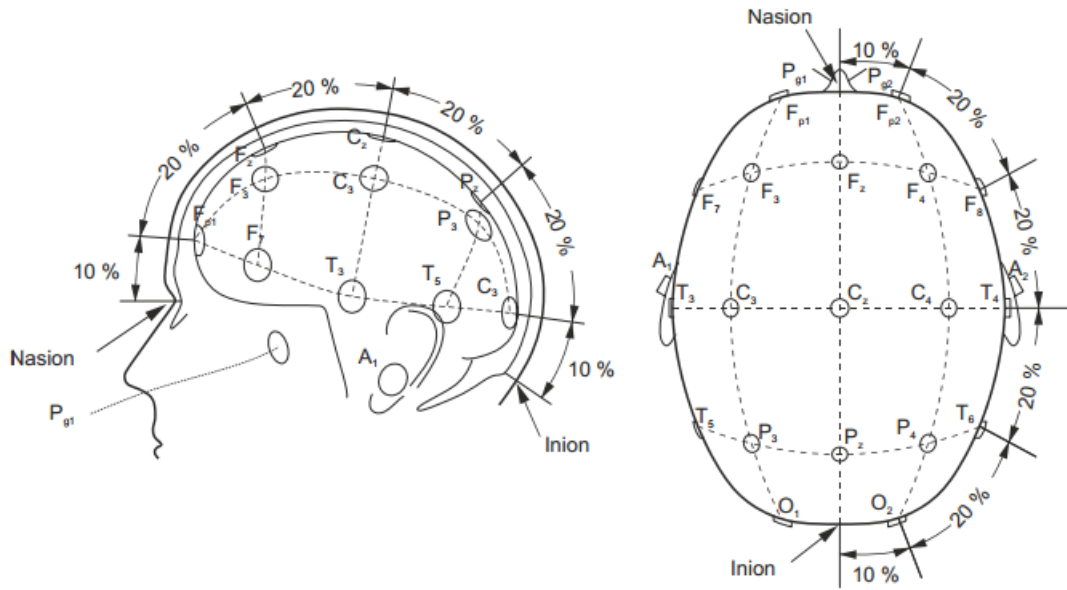


Figure 5: The International 10–20 System. From (NICOLAS-ALONSO; GOMEZ-GIL, 2012).

The NeuroSky devices have their sensor placed at the point Fp1 according to the System, while the Emotiv Epoc device’s sensors are positioned at the points AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8 and AF42. The other device has its sensors in positions Fp1 and Fp2.

It is worth mentioning that the aforementioned headsets appeared in the selected primary works in this study and were described for a better understanding of its results. However, they are not the only consumer-grade EEG devices available. Other commercial devices, such as those listed in the work of Ahn et al. (2014), are also available in the market for the general public.

2.5 Game Platform, Purpose and Genre

Similarly to BCI systems, a computer game can be classified according to many of its characteristics. According to the platform that the game is played, i.e. the game machine (ADAMS, 2010), it can be a (personal) **computer (PC)** game; a **console** game; or a **mobile** game. Computer games can also be categorized as **browser** (or **web**) games if they run directly in a web browser. They can also be classified by its purpose (ADAMS, 2009): **entertainment** games, which its primary objective is to entertain the player; and **serious** games, which have other purpose rather than entertainment alone (MICHAEL; CHEN, 2005), such as health care, education, advertisement, communication, scientific research and training (LAAMARTI; EID; SADDIK, 2014).

Health care serious games serve medical purposes, such as health monitoring, detection and treatment of diseases, therapeutic education and rehabilitation, as well as promoting physical exercise and healthier life styles (LAAMARTI; EID; SADDIK, 2014; JANARTHANAN, 2012). **Educational** serious games aims at teaching a specific subject to the player, such as arithmetic skills (GEETA; GAVAS, 2014), history (VOURVOPOULOS; LIAROKAPIS; PETRIDIS, 2012) and neuroscience (SCHWARZ et al., 2014), and can be used as an independent tool for learning or be employed in a classroom. **Training** serious games are similar, but aims at training the player to do a specific task (LAAMARTI; EID; SADDIK, 2014), such as military, medical or cognitive training. Also related, **communication** serious games aim at improving the communication and cultural skills of the player, such as learning the language or the culture of a foreign country. **Advertising** serious games, also known as "advergames", are designed to promote brands or products, and usually have shorter playing time and simpler rules in comparison to regular games (CAUBERGHE; PELSMACKER, 2010). Finally, other applications such as scientific **research** serious games are developed to be employed as a tool to conduct scientific experiments, e.g. validate a new technique or verify a test hypothesis.

A common taxonomy for games is to classify them according to its common challenges and the gameplay characteristics. This classification based on gameplay interaction rather than visual or narrative differences is called game genre (APPERLEY, 2006). There are seven main genres that the games can be classified (ADAMS, 2010): action, adventure, RPG, strategy, puzzle, simulation and sports, each described below.

The **action** genre comprises fast-paced games with time-critical challenges. They usually involve gameplay that test physical skills of the player, such as hand-eye coordination and reaction times (MARSHALL et al., 2013). Many popular genres derive from the action genre, such as First-Person Shooters (FPS), platform, arcade and fighting games. Action games became and continue to be one of the most dominant and popular genres since the 1990s (WOLF, 2012). **Adventure** games focus on a central story that develops as the game advances, with elements of exploration and often requires puzzles to be solved in order to proceed. There can also be multiple story arcs for the player to choose, and the gameplay is based on the decisions that the player make during the story. **Role-Playing Games (RPG)** are similar to adventure games in the sense that the game revolves around a central story, the difference bring that in an RPG game the player takes the role of a specialized character, which can progress and get stronger by a leveling system, usually through battles with monsters and other characters. An RPG can be turn-based, in which the combat occurs in alternating turns, or with real a time battle system.

Strategy games focus on carefully planning a series of actions, thinking and conducting a strategy to win the game. The player is usually put against one or more opponents and must defeat them by exploiting their mistakes and applying a better strategy. Strategy games can be turn-based, like the classical board games or real-time, also known as RTS (Real-Time Strategy). The **puzzle** genre focus on problem solving, generally through logical thinking, deduction, pattern recognition, word completion or any other problem-solving skill. Players may be required to manipulate objects, colors, symbols or shapes in order to achieve a specific pattern. A game belonging to the **simulation** genre tries to simulate aspects of a real or imaginary activity or situation. They can be further classified according to what is being simulated: life simulation, or artificial life; management and construction simulation, or vehicle simulation. Lastly, the sports genre, as its name implies, comprises games that simulate a real or imaginary sport, with the same set of rules and conditions.

A game may not be limited to one specific genre alone. Action-Adventure games, for example, incorporate elements from both genres. It is not unusual for games to mix elements from other genres to create a unique gameplay. They are usually classified by their most prominent characteristics. If the game is predominantly based on action and fast-paced elements, it can be classified as an action game. The sport genre can have elements from both action and simulation games, but the most prominent characteristic is that it simulates a sport. Although adventure, RPG, simulation or strategy games may incorporate puzzles in their gameplay, only games that focus on the problem solving as the primary gameplay activity are classified as puzzle games (ADAMS, 2010).

3 Systematic Literature Review

This chapter reports the process and results of a Systematic Literature Review (SLR) of consumer-grade EEG, BCI-based games. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (MOHER et al., 2009; LIBERATI et al., 2009) served as a guideline for this report. The study focuses in the following Research Questions (RQs):

- **RQ1:** What kinds of games are created using consumer-grade EEG technology? What are the characteristics of such games?
- **RQ2:** Which BCI control signals those consumer-grade EEG mind-controlled games are based upon? Which are used more and why?
- **RQ3:** How are those games evaluated? Is there any effort to make those games more user-friendly and accessible for the players? And how difficult it is to play them?
- **RQ4:** What are the gaps and open topics in the field?

The motivation for the RQ1 is to understand the current scenario of games developed using consumer-grade BCI technology, how and why such games are developed and how they differ from regular games. Understanding the characteristics of such games may also indicate which techniques, game genres and gameplay styles works well with BCI technologies and which do not. In contrast with RQ1, that focus on the games itself, the RQ2 is related to which BCI techniques are employed to develop such games, and what paradigms are used more often. Given the limitation that the consumer-grade devices may have in terms of technology, it is expected that there is some level of adaptation of the gameplay in order to control the game in an intuitive way. The answer to this question may reveal some tendency to adopt certain kinds of BCI paradigms in order to control the games.

The motivation for the RQ3 is to understand how those games are evaluated, not only quantitatively but also qualitatively. Also, if there are any concerns about the user

interaction and efforts made aiming to make the interaction more natural to the user, i.e., that the players will actually enjoy the game and be motivated to play it, rather than the game being a technical implementation alone. Finally, RQ4 is related to the gaps and open topics in the field of consumer-grade, BCI-based computer games, i.e., what are the challenges, research opportunities and problems that must be faced in order to improve the overall quality of such games.

3.1 Methods

The systematic review was conducted and structured following strict guidelines. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (MOHER et al., 2009; LIBERATI et al., 2009) was adopted as it provides a clear direction for the reporting of systematic reviews and meta-analysis. The PRISMA methodology was widely applied in fields such as health, technology, and environment for gathering comprehensive literature reviews (ZARE et al., 2016; BRZAN et al., 2016; MERONE et al., 2017; CAUWENBERG et al., 2011; COOK et al., 2011; SYMONDS et al., 2017). The PRISMA states three main steps to perform a SLR, i.e. literature search, selection of eligible papers, and data extraction and summarizing (ZARE et al., 2016).

3.1.1 Eligibility Criteria

The eligibility criteria adopted in this SLR is focused on BCI games that uses consumer-grade EEG devices as a control channel, i.e., the EEG data captured from the headset has been used to actively or passively control any aspect of the game, such as camera/character movement, environment or difficulty. The selected consumer-grade devices for this study were any device from NeuroSky or Emotiv, due to their popularity and availability, as stated in previous sections.

3.1.2 Information Sources

Two main search engines were used as base for the search process, i.e. Scopus and Web of Science. These two engines indexes relevant digital libraries in the field of computing and engineering, such as IEEE Xplore Digital Library, ACM Digital Library, Springer and Elsevier. These digital libraries provide peer-reviewed articles from journals and conferences. The Google Scholar search engine was also used to find relevant papers that may not

have been indexed in the aforementioned bases. The search engines and its addresses are listed in Table 1.

Table 1: Search sources.

Source	URL
Scopus	https://www.scopus.com/
Web of Science	https://www.webofknowledge.com
Google Scholar	http://scholar.google.com

3.1.3 Search

The search terms were defined by selecting keywords related to brain-computer interfaces, consumer-grade devices and games. The terms were divided into three groups, each group containing words that are synonyms or have the same semantic meaning in the field of BCI. Table 2 presents each group and the terms used in each one.

Table 2: Search terms.

Group 1 (BCI)	Group 2 (Technology)	Group 3 (Games)
BCI	NeuroSky	Game
Brain-Computer Interface	Emotiv	Entertainment
Brain-Machine Interface		Healthy user
Neurofeedback		Videogame
EEG		Gaming
Electroencephalogram		
Mind-controlled		
Brain-controlled		
Biofeedback		

The search string was defined by connecting every word within each group with a boolean OR operator, and then combining two groups by connecting the terms of each one with another operator. Group 1 and Group 2 were combined using the OR operator and the result was connected with the AND operator with Group 3. The resulting search string was, therefore:

("BCI" OR "Brain-Computer Interface" OR "Brain-Machine Interface" OR "Neurofeedback" OR "EEG" OR "Electroencephalogram" OR "Mind-controlled" OR "Brain-controlled" OR "Biofeedback" OR "NeuroSky" OR "Emotiv") AND ("Game" OR "Entertainment" OR "Healthy user" OR "Videogame" OR "Gaming")

The first two groups were connected using the OR operator to allow for consumer-grade devices from other companies to appear in the search. The search in the literature was performed manually using the search string within the search engines shown in Table 1, set to search the terms in the title, abstract and keywords of the articles. The search was performed in the period of September 24–27 of 2016 in the Scopus engine; from September 30 to October 04 in the Web of Science engine; and in the period of October 06–08 in the Google Scholar engine. As the Google Scholar returned over 10,000 results, only the entries from the first 35 pages of search were considered, having 10 entries per page.

3.1.4 Study Selection

For every paper found in each digital library, a series of criteria were applied to narrow down the results to a set of relevant articles in the area for answering the research questions. The adopted Selection Criteria (SC) were:

- **SC1:** Articles written in English;
- **SC2:** Articles published in peer-reviewed scientific journals or peer-reviewed scientific conferences;
- **SC3:** Articles published during the period of January 2007 to April 2016;
- **SC4:** The title or the abstract explicitly states that the main focus of the research is BCI-based games.

If the abstract provided little information about the research focus, the article was temporarily kept for further analysis. In this first stage, the quality of the papers was not addressed. The search period (SC3) was chose based on the release date of the first consumer-grade BCI device. The selected articles were then analyzed for their content, as part of the Exclusion Criteria (EC):

- **EC1:** The main focus of the article was not related to BCI-based games;
- **EC2:** Used exclusively another bio-signal other than brain waves;
- **EC3:** Did not used any consumer-grade EEG BCI device;

If any of the EC were met, the article was eliminated from the results. The remaining papers were further analyzed for their context, as part of the Inclusion Criteria (IC):

- **IC1:** The consumer-grade EEG technology was used to actively change or control any aspect of the game;
- **IC2:** The consumer-grade EEG technology was used to passively change or control any aspect of the game;

If the article did not meet any of the IC (e.g. the brainwaves signals were used only as an evaluation instrument other than a game control), the article was eliminated from the results. The selected papers then underwent a quality screening. The following Quality Criteria (QC) were adopted:

- **QC1:** Are the goals of the research clearly stated? Are they related to the development, use, evaluation or applications of the game or the BCI?
- **QC2:** Is the developed or presented BCI-based game the primary focus of the research?
- **QC3:** The interaction, methods, paradigms, tools and technologies are clearly described?
- **QC4:** An experiment or case study was conducted to evaluate the game or validate the methods adopted? Is this evaluation well described?
- **QC5:** Are there any conclusive results regarding the use of the adopted technologies/methods? Are the main findings clearly described?

All the articles were analyzed by the researchers, which answered "yes", "partly" or "no" to whether each criteria was met by the article. A score was attributed to each paper according to the numerical sum of each quality criteria: each "yes" translated as 1.0 point, "partly" as 0.5 point, and "no" as 0 point. Therefore, each paper received a score that ranged from 0 to 5 points. All papers which the total score was equal or greater than 3.0 were included in the final selected studies used in this work. Table 3.1.4 further describes the complete description for each score of each quality criteria.

Table 3: Quality criteria scores.

Quality Criteria	Score	Description
QC1	0	The aims are not clear and not related to the game or the BCI.
	0.5	The aims are clear, but not related directly to the game or the BCI.
	1	The aims are clear and related to the game or the BCI.
QC2	0	The game is not the focus of the research nor is related to it.
	0.5	The game is not the primary focus of the research, but is directly related to it.
	1	The research is built around the game itself.
QC3	0	It is not clear what technology, methods, paradigms and tool were used, nor how the interaction was performed.
	0.5	The technology, methods, paradigms and tools are well described, but the BCI interaction with the game is not clear.
	1	All the aspects of the BCI interaction are clear and well defined.
QC4	0	There was no evaluation. The article only presents the game or the methods.
	0.5	There was an informal/uncontrolled study to access anecdotal and/or qualitative data regarding the interaction with the game.
	1	A controlled experiment, case study, comparative study or quantitative evaluation was performed as means to access the quality of the BCI interaction.
QC5	0	The authors did not reach or presented any conclusive results regarding the BCI interaction in the game.
	0.5	The findings are clearly described, but there are no conclusive results regarding the BCI interaction.
	1	The findings are clearly described and there are conclusive results regarding the adopted technologies/methods.

3.1.5 Data Collection Process and Data Items

After the inclusion process was finished, each article was accessed in more details to extract key data as part of the synthesis stage. The data extracted were the following:

- The authors' information: names, institutions and country;
- The source and full reference;
- Summary of the study;
- Technical aspects of BCI games, such as:
 - The BCI control signal(s) employed;
 - Which equipment were used;
 - Which development tools were employed;
 - The game(s) genre;
 - How the EEG data was used as a control mechanism.
- The evaluation that was performed and its data, such as:
 - Number of participants;
 - Quantitative analysis and its tools;
 - Qualitative analysis and its tools.
- Findings and conclusion.

The data extraction and the verification of the resulted data were performed by the researchers. A data collection sheet was developed, tested with ten random studies and refined in the process. One of the researchers performed the data extraction from the selected studies while the other checked and validated the extracted data, article-by-article. If there were any disagreement, they were solved by discussion between the researchers.

3.2 Results

The results are presented both in the perspective of the search itself and the games' characteristics, such as general data regarding the game mechanics and the BCI interaction, as well as an individual description of each reviewed game.

3.2.1 Study Selection

A total of 1,641 articles were initially found as potentially relevant after the search in the Scopus and Web of Science engines. 620 more articles were found through the Google

Scholar search engine, thus totaling 2,261 initial papers. A total of 372 duplicate results were excluded before the application of the selection criteria, resulting in 1,889 articles. After the title and abstract review of the remaining papers in the first step of the selection criteria, 1,260 articles were excluded, decreasing the total to 629. The full text of the remaining available articles were revised for the second stage, the exclusion criteria, and 516 articles were excluded, 29 of these for being not available (NA). The 113 remaining articles went through the inclusion criteria and 39 more were excluded. The remaining 74 went to the quality criteria stage and more 24 articles were excluded, leaving a total of 50 papers for processing in the data extraction step. The average score in the QC stage was 3.39, with a standard deviation of 1.03. Therefore, there were a total of 50 articles included in this work. The summary of this process is illustrated in the PRISMA flow diagram in Figure 6. The list of all 579 excluded articles (by NA, EC, IC and QC) is presented in the Appendix B.

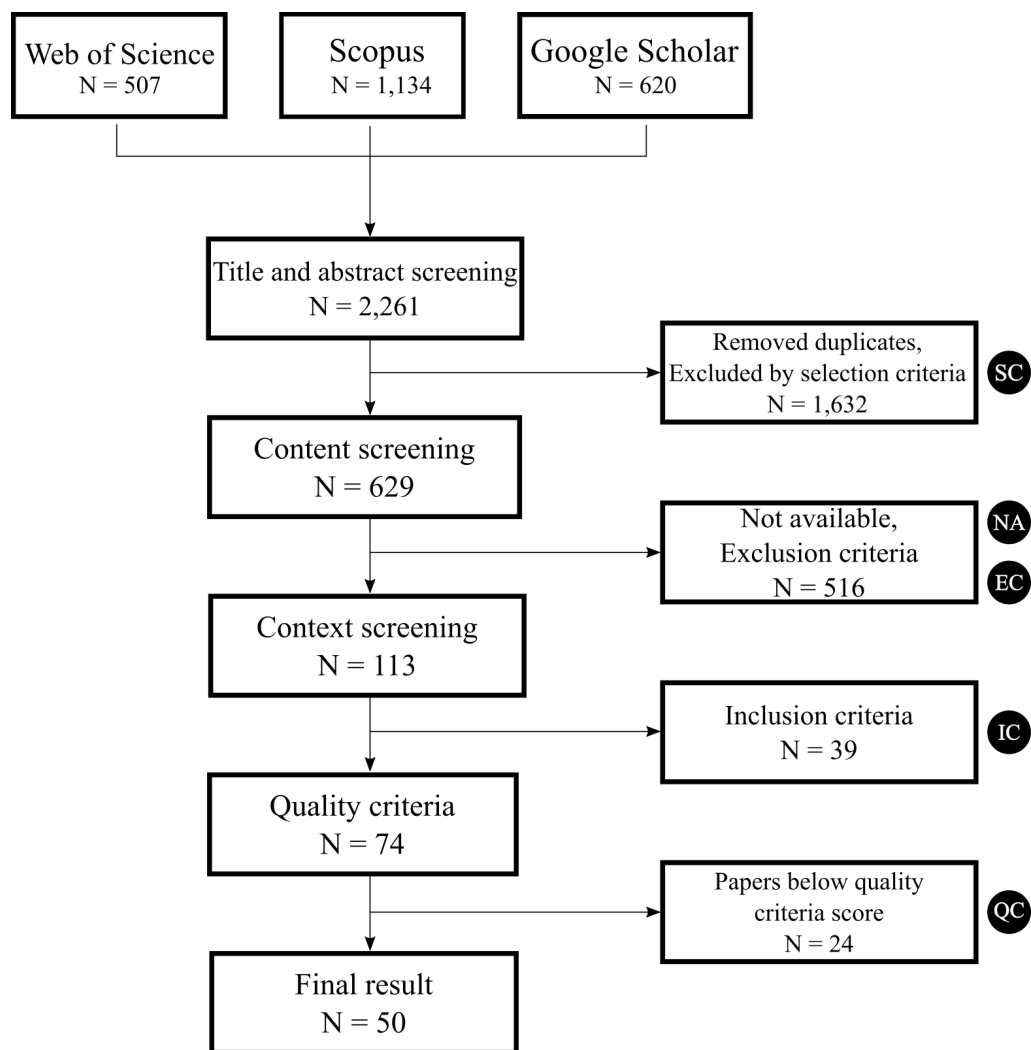


Figure 6: PRISMA flow diagram.

It is important to notice that although 50 articles were selected, some of them described multiple games (one paper described two games (SCHWARZ et al., 2014), another described three (ANTLE et al., 2015)) and some papers (seven in total) related to the same game. Being so, after the data collection process, 46 games were listed (G1–G46) in total (50 articles minus seven repeated plus three extras in two articles). Table A.1, available in the Appendix A, summarizes the basic data of all reviewed games from the perspectives of both the BCI interaction and the game itself. Additional data from the games can be found in Table A.2.

3.2.2 Study Characteristics

The selected studies and their respective games were classified according to the data collection process, specifically to the technical aspects of the game(s), such as which headset was used, the control signal(s) used, how the brain signals were used as a controller and the game(s) genre.

In relation to the employed headset, from the 50 selected studies, only one used both headsets to control its game. From each game perspective, 28 used the Emotiv Epoc headset (59.57%), ten used the NeuroSky MindWave (21.28%), seven used the NeuroSky MindSet (14.89%) and two used the other device (4.26%), for a total of 47 (46 games, one with two headsets). Figure 7a gives the chart for each headset usage. The relation of the number of games published by year and the employment of each headset device is shown in Figure 7b. Only the games were considered, not the actual papers describing them. In the cases where two or more papers described the same game, only the first one was considered. It is important to highlight that the 2016 column only considers works published until April of that year.

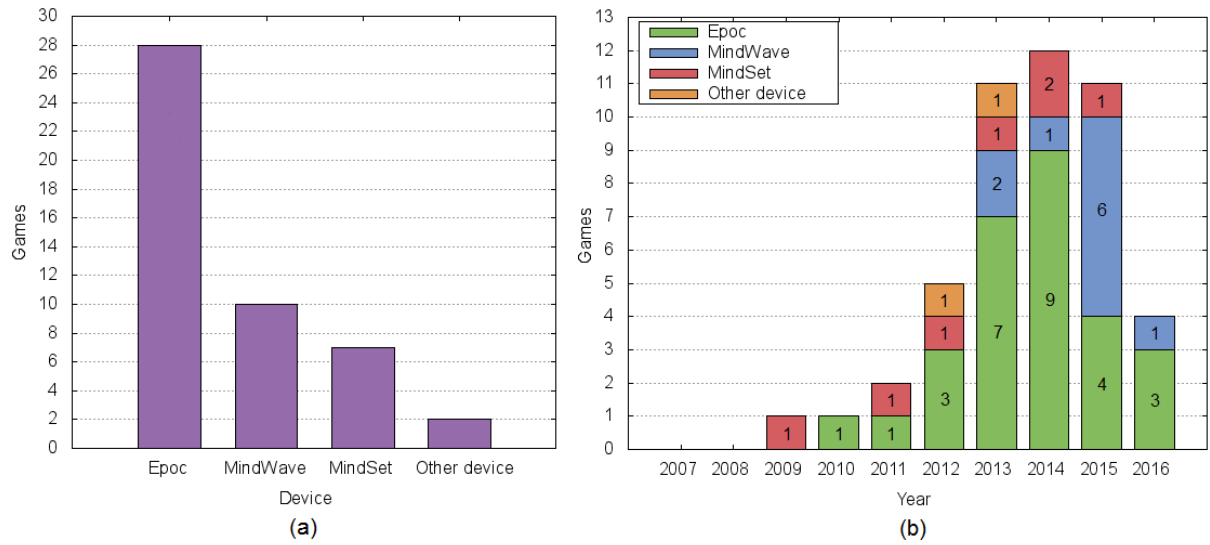


Figure 7: Number of games (a) using each consumer-grade EEG device; and (b) published by year.

For the control signal, eight types of control were predominant: Attention (35.00%), Meditation (20.00%), Motor Imagery (16.67%), SSVEP (11.67%), Emotions (8.33%), Blink (5.00%), Eye Tracking (1.66%) and VEP (1.66%). The chart in Figure 8a summarizes this classification. Note that, although there are 46 games, 11 of them use two control signals and one uses four control signals (multimodal games), so there are a total of 60 entries in the graphic.

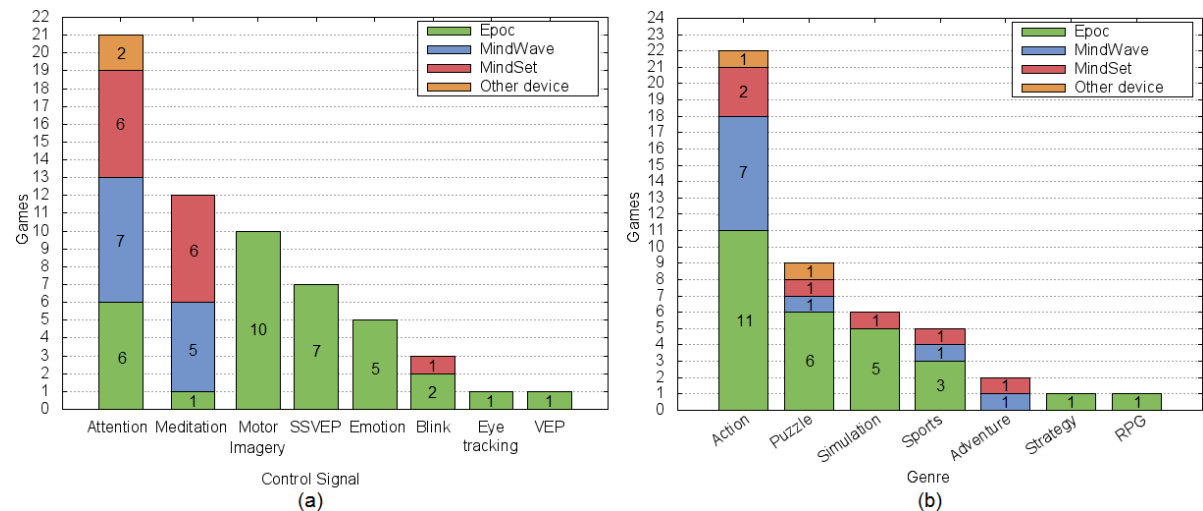


Figure 8: Number of games (a) using each control signal; and (b) of each genre, both stacked by EEG device.

As for the games' genre, there was a vast diversity, but a clear dominance of certain genres over the others. The genre with most developed games was the action genre with

almost half of the reviewed games (22 games, 47.83%), which also includes FPS, platform and shooter games. The puzzle genre follows next, but with less than half of the games (nine games, 19.57%), followed by simulation games (six games, 13.04%), including vehicle and life simulation games, and the sports genre next (five games, 10.87%), which also includes racing games. There were two adventure games (4.35%), one game for strategy (one tower defense game) and one game for a Massive Multiplayer Online RPG (MMORPG). This distribution is shown in Figure 8b, stacked in relation to the device employed.

The games were also classified according to various technical aspects collected in the data processing stage (available in the supplementary material). In relation to the number of players, only five of the 46 games (10.87%) are multiplayer games and only three (6.52%) can be played over a network. The platform also shows a predominance of the PC, with 39 (84.78%) presented games, against six mobile games (13.04%, three for smartphones and three for tablet) and only one web game. As for the development of the games itself, 34 of the selected games (73.91%) were actually developed, while the remaining 12 (26.09%) were existing games adapted for BCI control. Finally, as for the necessity of training for the system to work, 22 games needed a training phase (47.83%), while 22 did not need any training (also 47.83%). Two papers did not inform whether the training phase was required. Not much data were available about the development platform, tools, programming languages or frameworks employed, but from the 18 papers that mentioned which engine were employed, 13 used the Unity platform for development.

As for the purpose of the game, 13 games were developed to be employed as a research tool (28.26%), while 11 aimed at training programs (23.91%), nine primarily for entertainment (19.56%), eight for health care programs (17.39%) and five as educational tools (10.86%). Figure 9a shows this distribution, stacked by headset (one educational game used two headsets, so there are 47 entries in the graphic). It is important to notice that a single game can have characteristics of multiple genres, as well as have one or more purposes. However, only the primary or most outstanding characteristics of the game were used to classify its genre and purpose, to avoid having multiple classifications for each game.

In relation to the evaluation data from the studies (available in the supplementary material, Table A.3), the majority of the studies (40 out of 50, 80%) employed an empirical strategy to evaluate the game or the players' interaction with it. From these 40 studies, 2 were surveys, 22 were case studies and 18 were (controlled) experiments. 19 out of the total 50 studies (38%) performed some kind of qualitative evaluation, while 36 out of

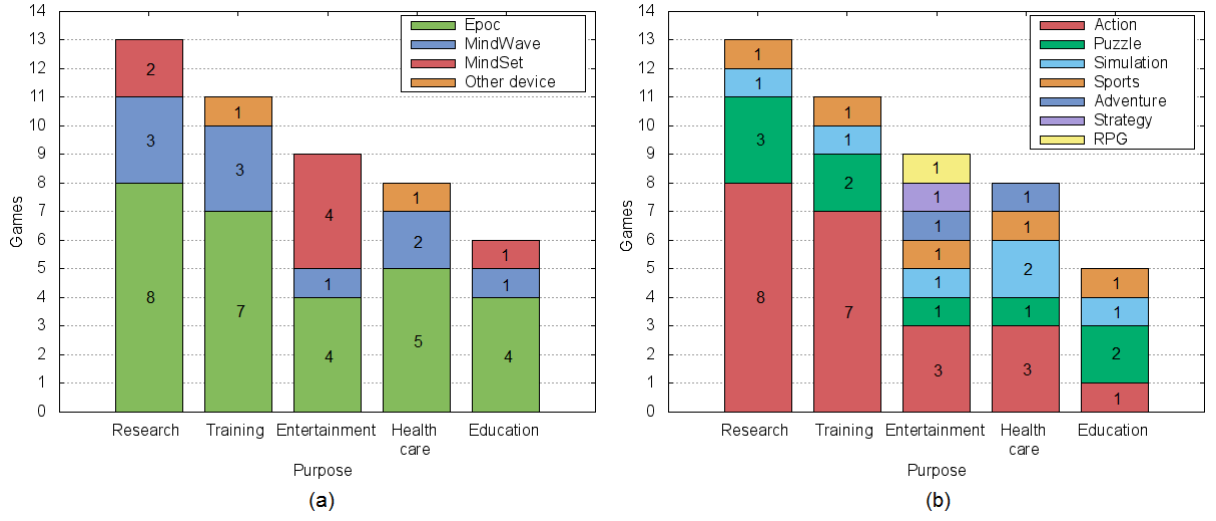


Figure 9: Distribution of games per purpose, stacked by (a) consumer-grade EEG device; and (b) game genre

these 50 studies (72%) performed quantitative evaluations. As for the number of subjects in the evaluations, from the 41 samples, the average number of subjects is 19.46 (mode = 3, $SD = 19.82$), while the average number of sessions is 3.51 (mode = 1, $SD = 6.71$). Table 4 shows the statistics for these data.

Table 4: Statistics of the games' experiments.

Variable	Average	Standard Deviation	Minimum	Maximum	Mode
Sessions	3.51	6.71	1	27	1
Subjects	19.46	19.82	1	73	3

3.2.3 Additional Analysis

A number of additional analyses can be drawn when crossing multiple data items. There was no direct relation between the game genre and the control signal employed. However, the way that the control signal was used to play the game had some similarities. The majority of games that employed the motor imagery as the control signal used it to control some sort of movement, while games using emotion adjusted the difficulty of the game according to the user's emotional state. The majority of games using cognitive effort defined a threshold for the attention or relaxation and a game action related to the user crossing or staying above/below that threshold, while some used it to adjust the game's difficulty, the speed or pace of the game and a minority used it to control the character's movement.

A few results were expected due to the nature of the BCI interaction and the limitation

of the headset devices. For example, most of the games using emotion and the game using eye tracking did not need a training phase. However, like the attention and meditation control signals, the training of the signal regulation is part of the game itself, as the user must learn to self-regulate his/her emotions or mental state in order to advance in the game. As expected, all games using NeuroSky devices employed attention and/or meditation as the control signal, and one also used the blink detection, which is also available in some versions of the devices. The other control signals were all employed by the Emotiv Epoc device, i.e., VEP, SSVEP, motor imagery, emotions, and eye tracking. It is also interesting to notice that all multiplayer games are based on the Emotiv Epoc device, while all mobile games employed a NeuroSky headset. Figure 10a shows the distribution of games per platform, grouped by consumer-grade device employed. Regarding the passive or active gameplay, only two of 27 games using the Epoc headset use the BCI as a passive control, with three more that can be played both passively or actively. With NeuroSky devices, five of 18 games use passive control, with one more that can be played by either ways. Figure 10b shows this distribution.

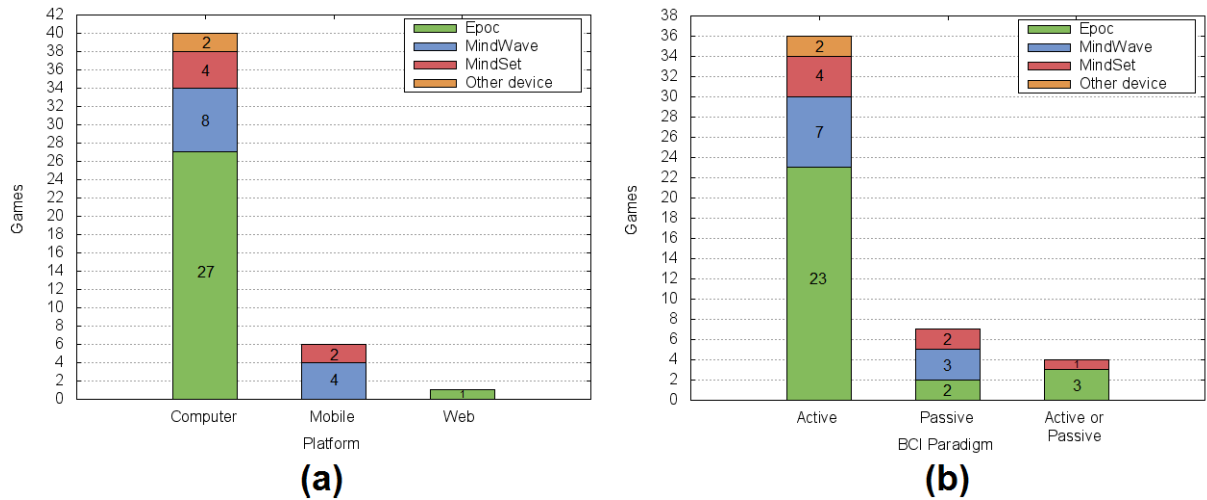


Figure 10: Distribution of games (a) per platform and (b) per BCI paradigm, stacked by consumer-grade EEG device

Also as expected, most of the Emotiv Epoc games need a training phase, as its control signals have a greater precision if a user training profile is created before using the game. Only four games based on NeuroSky devices need a training phase to adjust the attention or meditation threshold. There was also no direct relation between the headset and the game genre and between the game genre and the presence of a training phase. As for the purposes of the games in relation to their genre, the games which had entertainment as their main purpose also had the most diversity in genre, with at least one game of each

genre. The games with other purposes had action, puzzle, simulation, and sports games. Figure 9b presents this distribution.

Regarding the evaluation methods employed in the studies, the majority of the works that employed an empirical strategy used a case study scenario, which has less control over the variables than a controlled experiment process. Although many studies had their evaluation performed in a closed and silent ambient in order to avoid the influence of external stimuli in the captured EEG data, some evaluations were performed in noisy and busy environments, which are more likely to produce disturbance in the results, but are closer to real-life scenarios, in which the player may have less control over the environment while playing the game.

It is interesting to notice that some of the evaluations were possible (or were facilitated) to be performed due to the wireless capabilities of the consumer-grade EEG devices. In evaluations performed in public spaces, such as those presented in the works of Liarokapis et al. (2013) and Yoon et al. (2013), or those in which the subjects are children, such as the one presented in Antle et al. (2015), the wireless technology helps to decrease the discomfort for the user and allows for more freedom of movement, in comparison to the traditional wired EEG caps.

3.2.4 Individual Studies

Next, games are discussed by their individual characteristics, grouped by the control signal they have employed. When more than one control signal is used, the game is described in only one category, but cited in the others with additional details about the corresponding signal, if necessary.

3.2.4.1 Attention

Together with the games using the meditation control signal, the games using attention, i.e., in which the player's mental level of attention/concentration is used as input control to the game, compose almost half of the reviewed games (49.06%). The games which use this control signal are G1, G3, G4, G12, G13, G14, G15, G16, G18, G20, G21, G22, G25, G26, G31, G34, G37, G39, G41, G45 and G46. Seven of those games (G4, G13, G16, G20, G22, G26 and G46) also use the meditation levels of the player to control an aspect of the game.

G1 describes a game called Brain Chi, in which the user must concentrate in order

to increase his/her protection sphere and defeat the enemies that are attacking his/her character. G3 consists in a various mini-games which the player must complete in sequence to finish the game. In the first mini-game, the player must select four objects using his/her eSense attention score; next, s/he must climb a broken bridge, using the attention score to fix it; then, s/he must descend to a plantation of carrots and use the attention score to harvest the carrots.

G4 is a multimodal game also using a Kinect device to capture the movements of the player. The body movements are used to move the character in a 4x4 virtual board corresponding to the answer of a mathematical operation. If the player fails to provide the right answer, a robot starts approaching and must be eliminated using the attention score of the player. In G12 the health of the enemies are inversely proportional to the player's attention, while the background color of the scenario is used to represent this level of attention. G13 uses the eSenses to control a few characteristics of the environment, such as fog and lightness. The fog becomes denser when the meditation levels are low, and the environment becomes darker when the attention levels are low.

G14 is a FPS game in which the player must destroy robots that move around the scenario. However, the robots can only be shot if the attention score is above a threshold. G15 is an adaptation of the classic Snake game. The snake moves at constant speed and, when the player blinks, the snake stops and the attention score is calculated. If the attention is above a determined threshold, the snake turns right, and turns left otherwise. In G16 the eSense metrics of the NeuroSky device are used to control the movement of the character, i.e., the attention score controls the direction of the movement, while the meditation score controls the speed.

In G18, the attention levels of the player are used to build the game's scenarios. It is a platform game and, according to the player's performance and his/her attention eSenses, the next scenario's difficulty is modified. G20 is a mobile racing game, in which the player must control a car and finish a track using his/her eSenses. The attention is used to control the speed of the car: the higher the attention, the higher the speed. G21 consists of a 3x3 matrix that must be filled with pre-determined numbers. The numbers in their correct positions are shown before the match begins; then, each position is randomly selected, and the user must maintain his/her attention score above the measured threshold to be able to fill the position with the correct number.

G22 is an adapted version of the game Quake. Some variables that control the visual aspects of the game (such as the density and the color of the fog, the gamma and the

brightness) are altered according to the player's EEG (attention and meditation, and delta and theta waves), to simulate altered states of consciousness. In G25, the speed of the character, which must finish a track and collect objects, is directly proportional to the attention of the player. G26 is a mobile labyrinth game, in which the user must move his/her smartphone in order to conduct a ball to a specific destination in the map. If the attention or meditation levels are high enough, the player can open shortcut gates and get to the destination faster.

G31 is a musical game, in which the player must maintain his/her attention levels high enough in order to increase the speed of the music. The objective of the game is to end the music as fast as possible. G34 is a mobile phone called Mindninja, adapted from the popular mobile game Fruit Ninja, in which the player must cut the fruits while avoiding cutting the bombs. If the attention level of the player is low, the screen becomes fogged; otherwise, the game slows down.

G35, G36 and G37 are part of the same study, which aims to teach self-regulation to children living in poverty by increasing their levels of attention and relaxation. In G37, the game which uses attention, the player must concentrate in order to move a few stones into a basket. G39 is a multiplayer game in which the player's attention is used to gain certain advantages. The player must move in an open field and eliminate all the monsters that roam in the land in order to win. The attention levels are used to recharge his/her ammunition, health and increase his/her speed.

In G41 the player must play against the computer using his/her level of attention. Each player is a circle and must try to push his opponent out of the arena. The higher the attention level, the harder the player pushes his/her opponent. G45 is a card-pairing memory game, in which the player has to focus their attention in order to open or close the cards that appear on screen. G46 is an adventure game in which the player controls the character using standard mouse and keyboard controls, but the attention and meditation levels helps the player with some activities in the game; The higher attention level decreases the difficulty to aim and shoot at enemies, while high meditation levels make it easier to spot hidden objects and increases the recovering rate of the character. Table A.4 presents a summary of the games using the attention signal, with which BCI device was employed and which technique was used to calculate the player's attention.

3.2.4.2 Meditation

There are a total of 12 games which used meditation as a control signal, from which five used it alone (G28, G35, G36, G38 and G40) and seven used it together with the attention control signal (G4, G13, G16, G20, G22, G26 and G46).

In G4, the character's health increases when the user has a high level of meditation. In G13, the meditation levels control the density of the fog that surrounds the scenario. In G16, the meditation level controls the speed of the player's character, while the attention controls the direction of the movement. In G20, a racing game, the average meditation is used to determine the next track's difficulty: if the user is stressed (low meditation), the next course will be easier, and if the user is relaxed (high meditation), the next course will be harder. G22 also controls the density of the fog using the level of meditation of the player. G26 uses the attention and meditation levels to open specific doors in the labyrinth, which serves as shortcuts to the destination.

G28 is an adaptation of a popular RPG game called World of Warcraft. The player's character is a druid who can shape shift into a bear for close-ranged combat, or use magic for long-range combat. The level of stress (lower meditation) controls the transformation: if the player is stressed, s/he shape-shifts into the bear form. As commented in Section 4.4.1, G35, G36 and G37 are part of the same study. In G35, the player must relax while blowing a virtual pinwheel for a few seconds to increase his/her meditation levels. In G36, s/he must maintain the meditation level high enough to help a paraglider descend a hill and reach the ground.

The work of G38 describes a racing game, in which the meditation levels of the user controls the speed of the flying broom his/her character is riding. G40 is an adapted version of the Tetris game. The speed of the falling blocks is inversely proportional to the meditation level of the player, i.e., the more relaxed the player is, the slower the game becomes. In G46, the attention and meditation levels are used to decrease the difficulty in certain activities in the game.

It is interesting to note that most of the games using the meditation signal employed a NeuroSky device to do so. Only one game (G28) employed the Epoc device to use the meditation control signal, by calculating the relaxation estimation using the alpha waves. Table A.5, in the supplementary material, summarizes this data for the meditation games.

3.2.4.3 Motor Imagery

There are 10 games that used motor imagery as a control signal: G5, G6, G11, G12, G16, G17, G23, G27, G32 and G42. Five of them used it in addition to another control signal (G5, G12, G16, G23 and G27). G6 is a simulation game, in which the player must use the motor imagery to control the direction and movement of a virtual wheelchair in five different training scenarios. G11 is an adaptation of the Pong game called BrainPong, in which the player must defeat the opponent by bouncing the ball with his/her paddle into the other side of the arena. The up and down movement of the paddle is controlled by the motor imagery of each player. In G12, called EmoBlaster, the player controls a ship in a 2D grid and must defeat the enemies in the scenario. The enemies' health increases when the concentration of the player is low, and vice versa. The motor imagery command is used as a special ability to clear all enemies on sight. Also, the background color represents the current mental state of the player.

G16 is a simulation game set in ancient Rome called RomaNova, in which the player can move and interact with computer-controlled characters. The character's movement is controlled by both motor imagery and eye blink. In G17 the player is able to control a virtual robot both individually and cooperatively with another player using imagined movement. The robot is in a labyrinth and must reach a certain destination. The push imagined movement moves the robot in the direction it is heading, while the right hand imagined movement rotates the robot clockwise. G23 uses both SSVEP and motor imagery to control the rotation of pieces in a puzzle game. Each piece must be selected and rotated to the original position to reveal a hidden image.

In G27, the player must use the imagined movement of the left arm while also making the same movement physically with his/her arms. The objective of the serious game, designed to help in the rehabilitation of stroke patients, is to move a virtual arm and grab a ball in the scenario. G32 is an adapted racing game called TORCS, in which the control of the car is shared with the machine. In the game, the imagined movement of the hands increases the acceleration and the steering wheels angle. Finally, G42 is an adaptation of Second Life, a simulation game in which the user controls an avatar in an open world game, interacting online with other players and characters. The control is achieved using the imagined movement of the foot to walk and of the hands to go to left and right, respectively.

3.2.4.4 VEP and SSVEP

Seven games were developed using the SSVEP control signal: G8, G23, G24, G27, G29, G33 and G44. Naturally, all of those games used the Emotiv Epoc headset, as the NeuroSky devices cannot (usually) capture SSVEP signals. Also naturally, all of the games used the control signal in an active manner, as the user must gaze at the flickering stimulus in order to activate it.

In G8, a multimodal game using a Kinect device, the player must maintain this balance while destroying obstacles that come in his/her direction. The balance is controlled using the Kinect device and the obstacles flicks at a determined frequency, as the player must gaze at them to invoke the SSVEP signal. In G23, both motor imagery and SSVEP were used to control a puzzle game, in which the user must select each piece of an image and rotate it in order to reconstruct the original image. The eye tracking was also used, but not employing a BCI paradigm.

G24 is a tower defense game, in which the player must build towers to attack the enemies that come from one side of the board and prevent them from reaching the other side. In the game, each construction site is highlighted for two seconds, and the player must look at the stimulus when the desired option is selected. G27 used the SSVEP in a passive manner, as the motor imagery was the active control. The background flashed at a certain frequency to invoke SSVEP signals and increase mental activation in order to better capture the motor imagery signals. In G29, the player control a space ship composed of three parts, i.e. two "motors" and a weapon, each being the stimulus for the SSVEP flashing at different frequencies. Gazing at a motor will rotate the ship at the corresponding direction, while gazing at the weapon will cause it to shoot. The objective is to destroy as many enemies as possible.

Both G33 and G44 use four stimuli at different frequencies to indicate four directional commands, i.e., up, down, left and right. In G33, the player must control a cart and reach multiple destinations in the shorter time as possible. In G44, the player must reach a single destination in a maze scenario. G30 is the only game that used VEP alone. In the game, the user must perform simple mathematical operations, selecting the correct answer for the operation by looking at the corresponding option, which is a rectangular figure with a blue or red background and the answer in the center. The BCI system can distinguish whether the player is looking at each of the options by means of the background color.

3.2.4.5 Emotion Recognition

Five games employed the players' emotion as a control signal, four using it as the only BCI control (G2, G7, G9 and G10) and one also using motor imagery in addition (G5). G2 is a multimodal game intended for rehabilitation, and uses a combination of a haptic and a BCI device, i.e., Emotiv Epoc. In the serious game, the player must use the haptic device to grasp objects and place them inside a basket. The weight of the objects and the height of the basket are variable, and varies according to the difficulty. By reading the player's emotion using the Emotiv Epoc, the game decides whether the next stage will be harder (predominant positive emotions) or easier (predominant negative emotions).

In G7, the player's emotions are analyzed and, according to the level of difficulty, the player must change from one emotion to another, with the objective of learning to control his/her emotions for artistic expression. The game presents an affective image and a background color related to the target emotion. In G9, the player is in the role of a bartender and must receive and memorize the orders and names of customers. The player's emotions are used to control the difficulty of the game: if a negative emotion is predominant, the next level will be an easier one, and vice versa. G10 was also implemented for emotion regulation training: the player must maintain his arousal level in the desired state in order to avoid the increase of the game's difficulty. Specific elements of the game are distorted to increase its difficulty, such as the aiming blurring of the target, and distractors.

G5 is a game developed aiming to help people suffering from dyslexia, and its objective is to hear a word and choose the option corresponding to the word's spelling. The emotion is also used to control the difficulty of the game in real time: three or more options are presented to the player, and in the occasion of the predominant emotion is a negative one, one of the wrong options is "closed" to facilitate the choosing of the right answer.

3.2.4.6 Eye Tracking and Blink Detection

In total, four games used eye tracking and/or blink detection as its control signal, mainly or secondarily: G15, G16, G19 and G43. G15 is the classic Snake game, in which the player must capture food in the scenario without touching itself. The blink is used in conjunction with the attention level of the user, using a NeuroSky MindSet as the acquisition device. The snake moves at a constant speed and, when the user blinks, it stops and the attention score of the user is calculated, and the direction of the next movement (left or right) is

decided according to the attention score.

G16 used the eye blink to control the direction of the character's movement in an adapted simulation game. The cognitive functions of the player are used to control the forward and backwards movement, while the blink controls the left and right movements. G19 is also an adapted game. The player uses an Emotiv Epoc device to track the direction of the eyes; the direction (i.e. up, down, left or right) will correspond to the respective arrow in the keyboard, which will control the next movement in the game. G43 is a labyrinth game in which the player, controlling a cart moving at constant speed, must reach a certain destination using only the eye blink. The developed classification algorithm can detect if the user is blinking using his left or right eye, and the direction that the cart will rotate depends on which eye the player blinked.

3.3 Related Surveys

There are a number of past reviews that addressed the use of BCI technology, both for games and other general applications. This section briefly describes some of the surveys in the literature that focus on the use of BCI for games. Bos et al. (2010), for example, provides the state of the art of BCI games using neurofeedback, motor imagery, P300 and SSVEP. A total of 36 games and virtual reality systems were listed and described. It is commented that, in general, the pace of these games had to be reduced to allow BCI control, e.g. fast-paced games had to be converted into slow-paced, turn-based games. In addition, an investigation of usability aspects of BCI systems in the context of BCI games, such as learnability, memorability, efficiency, effectiveness, error handling and satisfaction, is also provided. For the learnability, for example, it is perceived that the users have to go through a long phase of training to use a BCI system. One of the challenges that are pointed out is that both the mental state of the player and the use of various brain functions, such as speech, vision and motor activity may have influence in the captured signal. It is also highlighted that applications of brain-computer technologies for healthy persons still have many obstacles for being usable in real-world environments.

Ferreira et al. (2014) present a literature review of BCI-based digital games, aiming to analyze the interaction design of these games and to identify limitations and implications related to BCIs design. The authors present a selection of researches that point out to a better understanding of the design of such games. The games are divided into four distinct groups, based on the detection method applied: neurofeedback, visual stimulus,

imagined movement and hybrid detection. The games were also categorized into their genre and number of players. Based on this research, a design rationale to support game designers in the process of designing BCI-based digital games was developed. Lotte (2011) discusses whether EEG-based BCI devices are suitable for 3D video games, describing the recent advances in BCI-based 3D videogames and its limitations, as well as its promising perspectives and the limitations of the current BCI technologies, mainly related to their usability and performance. Despite these limitations, it was proposed a number of areas in which these technologies could still be useful for 3D games, such as additional control channels and dynamically changing environments which react according to the user's mental state.

Marshall et al. (2013) summarizes a number of BCI games and evaluate the challenges that these games face in relation to their genres. Also, the gameplay mechanics used in the games are reviewed and evaluated considering their suitability in relation to the corresponding game genre. For each genre, recommendations for BCI game developers are provided. Observations were made regarding the use of BCI as a way to make small activities in the game significantly more entertaining, and development paths that had yet to be explored were highlighted, such as creating a game which its objective or difficulty changes depending on the user mental state, using passive BCI control, or adapt more existing games to use BCI technology. Also, it is stated that the user experience is also limited to this technology, as the translation algorithms' accuracy are yet to be improved and the player needs training, in the case of active BCI control paradigm, to give the desired input to the system.

The authors in (NIJHOLT; BOS; REUDERINK, 2009) provide a state of the art survey of BCI from the context of games and entertainment. The possibilities for including BCI as an added modality to game design and the development challenges that this inclusion brings are discussed. It is discussed, for example, that a BCI system could be used to measure the affective state of the player towards the game and adapt its flow according to this affective state. One could also use a BCI system to allow direct control of the game by means of the user's brain signals. It is stated that games can be directly designed to be controlled by thought: the game environment could adapt itself to the cognitive and motoric skills of the player, as well as its mental state. Several challenges are discussed and examples of games and experiments related to those challenges are presented.

Ahn et al. (2014) conducted a literature survey of BCI games, administered questionnaires to different groups of users and gave game demonstrations in order to obtain

feedback before and after they play the games. The methods that were designed to address certain questions which must be answered in order to BCI games to become popular are also described. The results of the survey are presented along an interpretation of which control paradigms are appropriate for BCI games, the public's awareness of BCI's usefulness, and if the people believe or not that BCI is available in the market or how many years it is needed in order to develop the BCI technology in order to. Also, through a questionnaire administered to a number of participants, among users, researches and game developers, the elements which are important in the development of BCI games were investigated and discussed.

Each of the described surveys approached the applications of BCI in games from a different perspective. Some search data may vary among studies, such as the number of papers published in each year in the same period of search. This is due the differences in the search process, such as the databases considered, the keywords and the rigor in filtering the most relevant works. However, it is important to notice that, aside from directly affecting the results, not employing a rigid and precise search process hinders the reproducibility of the results, which is essential for a scientific research. Some of the challenges and characteristics described in the related surveys will be discussed in the next session, taking in consideration the results of this work.

3.4 Discussion

This section discusses the results and main findings of the review. The research questions are addressed and reflections on the results are drawn based on the flaws and qualities of the analyzed games. Each research question will be addressed individually; then, the results of the review will be analyzed in comparison with past and related surveys in the field.

3.4.1 Research Questions

With the data from the reviewed games, it is possible to answer and discuss the research questions. These answers came from the analysis of all reviewed games and their characteristics, both in relation to gameplay mechanics and BCI techniques employed.

3.4.1.1 RQ1: What kinds of games are created using consumer-grade EEG technology? What are the characteristics of such games?

From the gathered data, there is no clear indication that the game genre of the developed games follows a specific trend in relation to the control signal employed. However, the main characteristics of such games can be analyzed to further understand the context in which these games were developed and with which objective.

It is clear that the vast majority of the analyzed games were developed with specific objectives in mind, not exclusively for entertainment purposes. Most of the games were used in serious applications, such as in the medical and educational field, or for conducting a specific research, such as to evaluate the performance of a new algorithm or technique. This is somehow expected, as the games were presented as a scientific finding in a research article. However, this also have an impact in the design, implementation and gameplay of the developed games. Firstly, the design of a game created to test a specific command, algorithm or control signal is not always a concern for the researcher. Many games found in the research had the minimal design for the user to be able to recognize the basic elements needed to complete a task. Secondly, the implementation may be biased in the sense of allowing the user to complete a task or an experiment, but only in a specific environment or in the presence of the researchers. Thirdly, the gameplay can also be affected by the control signal adopted in relation to the game genre or the action related to the signal. Often the gameplay, much like the design, is simplified to the minimum so the user is able to control the game with the adopted technique. Some exceptions are the adapted games, i.e., already existing games that had their controls or mechanics adapted to be used with the proposed BCI, such as G16 and G28. The advantage of such approach is that there was already a considerable amount of time and effort applied in the conception of the game and its design, and the researches need to worry only about the adapted gameplay mechanics with the BCI. Of course, there are also disadvantages related to the design and gameplay of the game itself; as the game was not primarily developed to be used with a BCI control, the new mechanics may not make sense for the user and must be carefully considered when adapting the control. Also, the design of the game may be heavily loaded and negatively impact the accuracy of the BCI system.

3.4.1.2 RQ2: Which BCI control signals those consumer-grades EEG mind-controlled games are based upon? Which are used more and why?

The predominant control signals adopted in the analyzed games were the attention and meditation. Of course, great part of this is due to the fact that the NeuroSky devices are predominantly capable of using these control signals and almost 40% of the games use a NeuroSky device. However, almost one third of the games that used the Emotiv device also applied one of those two control signals. This may be due the nature of the signal, which can be measured by simply reading the raw brain waves, applying an entropy calculation technique, such as sample entropy or fractal dimension, or by applying a ratio-based measure, such as the theta/beta or beta/alpha ratios to find the correspondent meditation or concentration level. Also, these signals are a reliable and well-grounded tool for neurofeedback training with positive results reported in various studies. One disadvantage of these control signals is that they usually require a greater temporal resolution to be used properly, as the cognitive state of the user changes every second and the average of a certain time window is usually calculated to be used as the meditation/concentration level. This may lower the pace of the game in the case of fast-paced games that requires fast reactions from the user. The two others most employed control signals were the motor imagery and the SSVEP. Both were used predominantly to control the movement of the player or to the selection of available options. This is somehow expected, as these signals are intuitive to use in those cases. Although the motor imagery is a signal that requires a more complex classification technique to properly work, the SSVEP is easily captured with a high precision even with low temporal resolution, which facilitates its use in games, but may also cause visual fatigue in the user if exposed for a long time.

3.4.1.3 RQ3: How are those games evaluated? Is there any effort to make those games more user-friendly and accessible for the players? And how difficult it is to play them?

In general, the majority of the analyzed papers performed some kind of evaluation with subjects to test specifics aspects of the games. However, it is clear that most works focused in the quantitative analysis alone, as only 21 of the 50 researches presented some kind of qualitative evaluation, such as questionnaires, interviews and self-assessment forms, while the majority (33 out of 50) performed quantitative and comparative analyses. This can be possibly explained based on the results of RQ1, as many serious games are created specifically to test new algorithms of techniques on the users, without any concern for the

entertainment aspect of the interaction. Nevertheless, it is clear that there was indeed a concern to make the games more user-friendly, especially those focused in entertainment, educational and medical purposes, in comparison to games created exclusively for testing purposes. It can be observed that many authors were concerned with the subjects being able to play the game in a natural and non-intrusive manner, as some of the environments were usually close to real-life scenarios.

As for the easiness of use, however, the games still require, in general, long training phases and preliminary testing from the players. Although this is possibly derived from the limitations of the BCI technology, it appears that most games would not be viable for the general public to play without the help of a professional or researcher to guide the player in learning how to use and configure it. This also is related to the results of RQ1, as the easiness of use and learnability is not the primary concern of most studies, especially those focused on testing purposes, as entertainment and educational games are usually more intuitive to play.

3.4.1.4 RQ4: What are the gaps and open topics in the field?

Based on the results of the systematic review, it is clear that there are numerous challenges and limitations that developers and researchers have yet to overcome when it comes to consumer-grade BCI-based games. Most of the challenges that need to be addressed for BCI-based games to become a feasible platform for fun and entertainment are related to not only the technology itself, but how the games are designed, how the gameplay is adapted and how reliable the control is from the perspective of the user. The first challenge is to employ BCI control in fast-paced games: BCI applications typically need a few seconds to collect, analyze, interpret and translate a brain signal into a computer command. This may abruptly disrupt the game flow and break the feeling of immersion in the game. Some games need up to eight seconds to fully translate a brain signal into a command, not taking into consideration the chance of misunderstand the user's intention caused by natural error rates. Games using a consumer-grade EEG device are especially vulnerable to this problem as they use fewer sensors (thus a smaller spatial resolution) than medical-grade devices. Knowing this limitation, game designers must take into consideration the time it takes to interpret a command and design the gameplay accordingly.

The second challenge is the design of the BCI game itself. The field of BCI is relatively new, as BCI technology emerged in the 1970's and only recently it began to be used as an entertainment tool; being so, designers and developers may have difficulties in

adapting a traditional control to a BCI one. When it comes to creating a new game, the developer has the advantage of being able to mold the gameplay according to the intended control signal. For a developer trying to modify an existing game the task may be harder, as the game has already been designed for a specific control scheme. Also, some specific control signals depend on visual and auditory stimuli to operate, which must be taken into consideration when designing or adapting an existing game. The P300, SSVEP and possibly the attention and meditation states are examples of control signals that may be affected by heavily loaded graphics or audios. The game designer must take in consideration variables such as the considered control signal, what the BCI will control in the game, how it will control and how the precision of the BCI system may be affected by the graphics and sounds of the game. Often, the games are simplified in a way that the user only sees or perceive the external cue necessary to capture the intended control signal. In this experimental setup, it is easier to measure the precision of the system, as it is in ideal conditions. In a real-life scenario, this precision can be greatly affected by the user interacting with other elements of the game and his/her senses sharing the processing load of both stimuli (from the BCI and from the other elements). This also constitutes of the third challenge, as more research is necessary to determine how game elements such as animations, game graphics, brightness, colors and audio may affect each control signal, especially those who are related to the visual/auditory stimuli but does not need them in order to function (e.g. attention and meditation).

The fourth challenge is related to the training phase. Some of the control signals require a training phase to increase the accuracy of the system, e.g. motor imagery and cognitive effort. However, not infrequently these training phases can take from 15 minutes to one hour, which may be considered acceptable in an experimental setup, but may become a burden to the player in a real-life situation. When the training phase is absolutely necessary, it is recommended to try to minimize the time it takes or to entertain the user while in this training stage. One suggestion to gamify the training stage would be to implement mini-games that would serve to guide the user and apply the training phase in the form of a small game. This is done, for example, in G28, in which the user plays a "basketball" game in order to train the control signal before the experiment. This can potentially decrease the load of the training from the user and make this stage more interesting. Of course, in some systems the training phase requires the user to stay still with his/her eyes closed, so it is not easy to gamify this step. However, the game could offer a virtual guide or assistant that would inform the user when to relax, when to close his/her eyes and a numerical score representing his/her individual threshold, encouraging

him/her to increase his level of attention/meditation. One interesting approach to this problem would be to, instead of applying a training phase before playing, adapt the game so the system trains and adapts while the user is playing. This could be achieved by dynamically adapting the difficulty of the game in the same rate as the user learns to play and the system creates a personalized profile.

3.4.2 Related Surveys

In general, the results obtained from the search are partially in accordance with related surveys in the literature. Marshall et al. (2013), for example, found similar results both in relation to the trend in adopt certain game genres and the tendency to create simplified games to be used as a tool for scientific experiments. The fact that games using consumer-grade EEG devices are having similar challenges to games using medical-grade devices is both positive and negative: it shows that the limitation is not exclusive to the technology employed, but how it is employed and for what purpose. It is positive in the sense that, although there is still a long way to go in order to BCI games to become popular and a reliable platform for entertainment, there can be confidence that most of the challenges are feasible to be addressed with the current technology. Clearly the limitations in the overall BCI technology plays a fundamental role in the performance, accuracy and reliability of the developed games, but the challenges that involves gameplay and game design aspects alone are passive to further development nevertheless.

Although, to the best of our knowledge, no other survey focused on games based on consumer-grade EEG devices, the predominance of certain game genres and application of the games in researches shows that these tendencies are common to BCI games in general, not only for those using specific devices. However, the advantages that the consumer-grade EEG devices offers in comparison to medical-grade ones specifically in the field of games may be a decisive factor in the next years, in the sense that, although medical devices present the state of the art in terms of BCI technology, they are not feasible to be used by regular players and outside medical and research applications. The reason for that, excluding the economic factor (medical equipment are much more expensive and harder to acquire than consumer-grade EEG devices), in a real-life scenario, a healthy user is unlikely to acquire a medical device and know how to set and use it without specialized knowledge or the help of a professional/researcher. Even a consumer-grade EEG device like the Emotiv Epoc has limitations regarding the use by the general public, as it requires a saline solution to decrease the impedance of the electrodes and usually takes no less

than 15 minutes to completely set up. In this matter, the NeuroSky devices have some advantage as they are easier and quicker to set up and use, even by casual players and the general public.

Another reason for the tendency to use consumer-grade EEG devices is the specialized knowledge not only to use the device, but to actually develop an application using it, i.e., there is a limitation not only for the users, but for the developers as well. Developing a "raw" EEG application requires the understanding of various specialized fields, such as signal processing, artificial intelligence and neuroscience itself. The consumer-grade EEG devices are capable of abstracting several layers of these processing and analyzing steps. This makes the development of said applications feasible even to game designers with only basic knowledge of BCI systems and its technologies. This is especially important in the case of games, as there are several other constraints that the game designers must take into consideration; the abstraction of the BCI layers makes consumer-grade EEG devices more viable for development in this sense, and this ease can be noticed in Tables A.4 and A.5, as more than half of the games that used the attention control signal and almost all that used the meditation signal employed a pre-processed brain wave data to do so, such as the eSenses. The emotion recognition, in the case of the Emotiv Epoc device, is another example. It is possible that, in the future, easy methods for acquiring other control signals such as the SSVEP and the P300 will become available in consumer-grade EEG devices as well.

3.4.3 Complementary Discussion

Additional observations can be made based on the results and the data derived from the review. Regarding the development purpose of the games and how they were employed and evaluated in the studies, one can notice that it is indeed rare to find a BCI game created with entertainment purposes only, but this is possibly due to the nature of the BCI field itself. As BCI is a relatively new field of research, especially when it comes to games, there are still many challenges that need to be overcome and variables that need to be deeply analyzed to better comprehend the nature of BCI interaction. Not only are the authors limited by the current technology, especially regarding consumer-grade devices (which usually have a lower accuracy and resolution than medical devices to allow for lower prices and accessibility), but the field of BCI and neuroscience itself have open topics that impacts the interaction with the general public, such as BCI illiteracy (VIDAURRE; BLANKERTZ, 2010) and the origin mechanics of most of the control signals,

which are still unknown. Being so, it is understandable that most of the published papers regarding games still tries to push the boundaries of the technology and to explore new techniques, signals and algorithms.

As for the design and implementation of the game, both a new and an existing one, it is recommended to try to use the appropriate control signal for the intended gameplay. Specific BCI control signals work better with the appropriate action in the game, i.e., if their modulation are intuitive for the intended control within the game. For example, it is intuitive to control the movement of a character in the game using motor imagery, as actions such as "push", "move right hand to the left" and "lift" are analogous to the direction movements of the character. However, other control signals are counter-intuitive to use for certain actions, such as using the attention or concentration levels to determine the direction of the movement. A recommendation to associate the right control signal to the intended action in the game is to search for controls that actually match the original paradigm of the control signal, i.e., for what purpose the control signal is used. For example, the most common neurofeedback training using attention and meditation levels is to determine the individual user threshold and encourage him/her to maintain his average level above this threshold; i.e., the control signal is related to the intensity of the mental state, thus, to control a variable also related to intensity, such as the character speed or strength, may be more intuitive than to control movement direction or to select options in a puzzle, for example.

Another recommendation is to design the game using a design rationale. A design rationale is a document that explicitly lists all the design decisions and the rationale behind each of them, including possible alternatives and the pros and cons of each one (LEE; LAI, 1991). By using a design rationale, the game designer can avoid possible gaps in the gameplay or in the general design of the game caused by strange interactions originated from poor design choices. In this context, for example, authors Ferreira et al. (2014) proposed and described a design rationale specifically for BCI games, which can guide researches, developers and game designers in the development process of BCI games of any genre, using a consumer-grade EEG device or not.

3.4.4 Limitations

The first key limitation of the systematic literature review is is the risk of bias within the processes of search and classification of the works, including the classification of partially subjective data, such as game genres and some of the quality criteria, which may be subject

to the author's opinion and experience. Also, although the systematic review process make it less likely that the results of the literature search are biased (KITCHENHAM; CHARTERS, 2007), it is not impossible that there is publication bias in the primary studies. Also, there are risks of incompleteness of the researched data, taken into consideration that the search process was done in specific search engines that may not cover all of the available literature about the topic of interest. In addition, potential relevant works may have been excluded due to unavailability of the paper for the author. However, when the paper was not available due to lack of academic access to the publisher database, authors were asked by e-mail and academic social networks to provide a manuscript, if possible. Although many of such authors responded and provided a manuscript, 29 papers were still excluded due to unavailability as there was no response from the authors.

4 The Influence of Graphical Elements on Users' Attention and Control

In this chapter, an experiment using an attention-based BCI game is described. This experiment aimed to analyze both qualitative and quantitative aspects of the subjects' interaction with the BCI platform and the game itself, focusing on the influence of the graphical elements on the player's attention. We also aim to analyze how the users perceive their control over the game and whether their performance changes over time. Based on these objectives, the study is guided by the following Research Questions (**RQs**):

- **RQ1:** Does the average level of attention of the players changes over time?
- **RQ2:** Does the game's graphical user interface (i.e. its animations and visual feedback) affect the average level of attention of the players?
- **RQ3:** How do the players perceive their attention-based control over the game?

The comprehension of the role that the visual feedback and animations play in neurofeedback-based games may help understand how the brain processes this feedback and how it influences the performance of the player, and may serve as guidance to BCI developers, researchers and game designers for future applications.

4.1 Methodology

The experiment was designed to evaluate a number of factors that could have influence on the subjects' average attention and their interaction with the game, especially with the game's graphical user interface. This section describes the methodology employed to perform the experiment.

4.1.1 Attention-based BCI game

Mental War is an open-source computer game, which was developed to be played with a NeuroSky MindWave headset. The NeuroSky MindWave is a low-cost device that uses a single electrode to read the electrical signals from the brain through the scalp. This electrode is positioned at the forehead (position Fp1 in the international 10-20 system (NIEDERMEYER; SILVA, 2005)) and allows the detection of a wide range of brain waves bands (e.g. theta, delta, alpha, beta and gamma). Using a set of algorithms called eSense, the headset is able to translate those signals in the level of attention and meditation of the user, both being a number between 0 and 100, inclusive, which measures how the user is concentrated or relaxed. It is also able to detect and filter unique brain waves patterns associated with muscle contraction, called Electromyography (EMG). The device uses these patterns to detect if the user is blinking his/her eyes.

The player is represented by an avatar and must maintain his concentration, i.e. the attention eSense value given by the headset, high enough in order to pull his opponents in a tug-of-war match. The attention eSense of the NeuroSky MindWave headset is used in the game as the force that the player applies in the opponent. The average of all attention values read over time is calculated for both sides, and the difference of the two is the resultant force that will drag the player with less attention to the middle of the arena. The first player to reach the middle loses the game. The blink detection feature of the headset is used to give the player a small force bonus when used.

The game allows for the player to play against the machine, which can be set to three difficulties (i.e. easy, medium and hard) and maintain an attention level according to this difficulty setting. Figure 11 show matches against the computer in the easy, medium and hard difficulty settings. The game interface has two focus bars (laterals), that shows the actual level of attention of each player; a force bar (top) that shows the resultant force; the blink charges (under the force bar), that shows how many times the player can use the blink bonus; two indicators that shows the headset status (top left and top right); and the players' avatars (center).

The game can also be played with two configurations, i.e. with the game's graphical user interface ("With GGUI"), which is the game with all graphical and sound elements, and "Without GGUI", in which the game has no sounds and the graphical interface is hidden by a black screen with only a red dot in the center (Fig. 11d). The sounds of the game are few: there is a sound effect for when the game begins, for when the player uses a blink charge and for when the game ends.



Figure 11: Mental War game matches with its graphical elements in (a) easy; (b) medium; and (c) hard difficulty settings, and (d) without its graphical elements.

4.1.2 Research Questions

The RQ1 was elaborated to investigate whether the game helps to improve one's attention over time, i.e., if the player learns to concentrate better and for longer times by playing the game. This is important as it guarantees that the players will be able to progress through the game as it gets harder, and certify that attention-related games, in general, are able to help the player to improve and better control his/her mental state over time.

For the RQ2, we define the graphical user interface of the game as its visual elements, such as the background, the players' avatars, the force bar, the focus bar and the blink charges, as shown in Figure 11a. The hypothesis is that these colorful and animated elements might somehow affect the average attention of the player, as he/she (i) could be distracted by those elements and lose his/her concentration; (ii) increase it by focusing on an animation or on a specific object in the scene; or (iii) be distracted by the visual feedback of the biological status of the player's mental state (i.e. the focus bar).

The RQ3 involves qualitative and emotive aspects of the players' interaction with the game. Its objective is to investigate whether the players actually feel like in control of the

game using his/her attention, and if this sensation of control increases over time. This is particularly important in the context of a BCI-based game because of the nature of the input: as the player controls the game with a biological signal, at first it may appear that the BCI input is random or that there is no control over it, which may possibly decrease the player's satisfaction and/or motivation to play.

4.1.3 Participants

The experiment was conducted with eight volunteer subjects (S1–S8), being seven male and one female. Participants ranged from 19 to 26 years (mean = 22.75, $SD = 1.85$). None had previous experience with BCI systems.

Also, to avoid any accuracy issues with the device employed to acquire the subjects' brain waves, the only adopted selection criteria was that the participant had no metal plate implants in the region of the forehead. As brain waves are electrical signals, metal implants could interfere, create noise, or completely block the signal acquisition.

4.1.4 Ambient and Materials

The same computer was used by all subjects for all sessions of the experiment. The experiment was conducted in a closed, climatized and silent room, in which only the subject and one of the researchers were present. The computer is a HP Compaq Pro 6305 SFF with an AMD A6-5400 3.6GHz processor, 4 GB RAM, Windows 7 64-bits operational system and a 19" monitor, adjusted to the users' height. All sessions were recorded with the participants' consent, using a Microsoft LifeCam HD-3000 connected to another computer, to avoid any possible performance loss in the game. The headset used to acquire the subjects' brain signals was a NeuroSky MindWave model MW001.

The Self-Assessment Manikin (SAM) (MORRIS, 1995) was employed for the third research question. The SAM is an instrument able to measure affective qualities of the subjects, and was used in this experiment to collect data on the users' self-perception of satisfaction, motivation and control (or dominance) in relation to the game. It is an instrument with a solid theoretical base in psychology and is frequently used in general emotion and gaming research to measure specific emotions of the participants (e.g. as in (CHANEL et al., 2011; HOOGEN; IJSSELSTEIJN; KORT, 2008; POELS et al., 2012)). Figure 12 shows the SAM form, with the scales representing satisfaction, motivation and control, respectively.

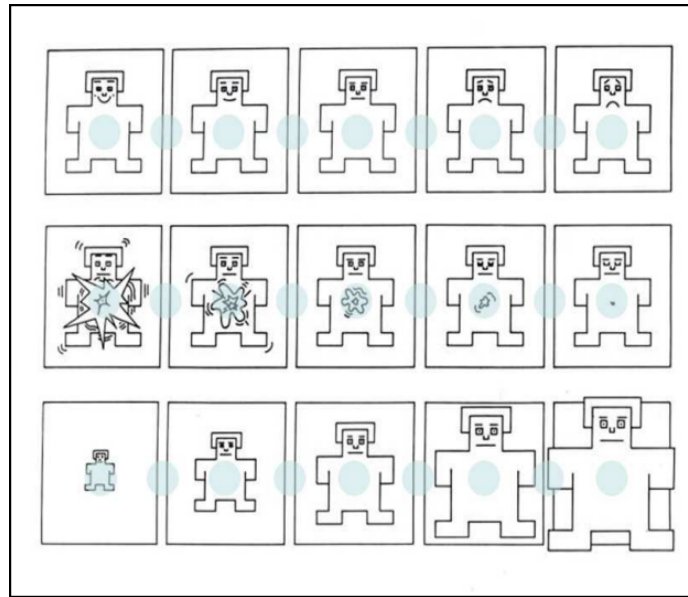


Figure 12: Self-Assessment Manikin (SAM)

4.1.5 Procedure

Each subject had to participate in six individual sessions of the experiment. Every session was recorded with a digital camera. In the first session, the subject filled out a demographic form and the researcher explained the experiment. The subject was free to ask any question at any time, and watched two videos that show how the game works and how it is played with the EEG device. The videos were used to assure that every subject received the same explanation about the game.

In each session, five matches were played, being the first one only for the calibration of the headset and for the subject to prepare for the following four; these first matches were excluded from the analysis. In the first three sessions (first round), the subjects played two matches with the GGUI, then two matches without the GGUI. In the last three sessions (second round) this order was inverted, being the first two matches without GGUI then two with GGUI. This inversion was made to minimize the influence of the subject's experience on previous matches of the same day in both interfaces, following the general experiment design principles described in (WOHLIN et al., 2012). Each participant played, therefore, a total of 24 matches, being 12 with GGUI and 12 without GGUI.

The matches in each session were all of the same difficulty, following the ascendant order, i.e. easy, medium, hard, then repeat. Table 5 shows the summary of this process. Each subject could only participate in one session per day, to minimize any possible influence of tiredness or emotional state in the subject's performance over the course of

many sessions.

Table 5: Procedure adopted for the experiment

Round	Session	Mode	Match				
			1	2	3	4	5
First	1	Easy	Calibration	GGUI	GGUI	No GGUI	No GGUI
First	2	Medium	Calibration	GGUI	GGUI	No GGUI	No GGUI
First	3	Hard	Calibration	GGUI	GGUI	No GGUI	No GGUI
Second	4	Easy	Calibration	No GGUI	No GGUI	GGUI	GGUI
Second	5	Medium	Calibration	No GGUI	No GGUI	GGUI	GGUI
Second	6	Hard	Calibration	No GGUI	No GGUI	GGUI	GGUI

At the end of match 3 and before match 4, a SAM form was applied to the subject in relation to those matches. Also, after each match, a short semi-structured interview was conducted with the participant to acquire relevant information about the match, such as what strategy he used to play, if he felt tired or fatigued, whether he found the match to be difficult, and general observations that emerged during the match. These interviews were used to assure that the subject would give more precise answers, as he had played the match just moments before. The experiment protocol is illustrated in Figure 13.

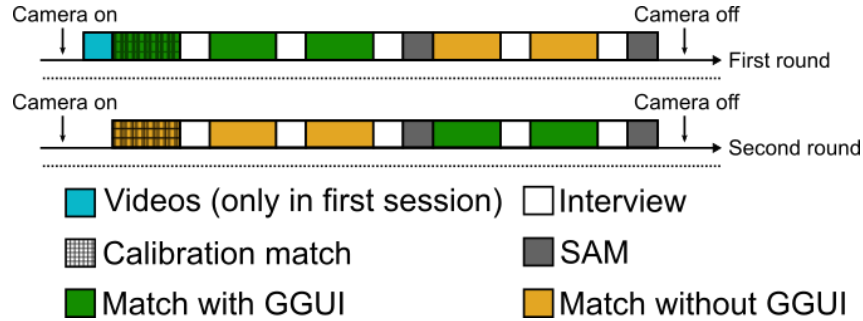


Figure 13: Experiment protocol

4.1.6 Design

The experiment was a 2x6 within-subject design (LEROY, 2011), as every user tested for each task. There were two independent variables:

- Game interface: with GGUI and without GGUI;
- Time: first to sixth session.

The dependent variables were the average attention of the participant and the match duration. The game interface conditions were counterbalanced using a 2x2 latin square (HINKELMANN; KEMPTHORNE, 2008).

4.2 Results

The results were divided and presented according to each research question separately. The analysis of the experiment data includes both quantitative and qualitative aspects of the interaction of the users in the 24 matches that each one played.

The quantitative results were obtained by applying a number of statistical analyses on the dependent variables, i.e., the output of the matches: the subject's average level of attention and the duration of the match. A D'Agostino & Pearson normality test was applied to guarantee the normal distribution of the values in all statistical analyses. The SAM was the instrument used to access the affective and emotional qualities of the subjects' interaction with the game. The SAM data were processed by assigning a numerical value for each point in the scale, ranging from 1 to 9.

4.2.1 RQ1: Does the average level of attention of the subjects changes over time?

To address this research question, the data from the two rounds of matches were compared according to the performance of each subject, i.e., their average attention. A two-tailed paired t-test was applied to find if there is a significant difference in the matches of the first and second rounds. The scores of the four matches of each session were averaged to represent the score of the session, resulting in three scores by each user for each round, thus totalizing 24 scores for each round. These 24 scores of each round were paired, therefore the degrees of freedom is $df = 24 - 1 = 23$. The null hypothesis is that the two means, i.e. μ^1 , the mean attention from the first round, and μ^2 , the mean attention from the second round, are equal. The t-test revealed that there is a trend to a statistically significant difference between the two rounds, $t(23) = 1.99, p = .058$, although the null hypothesis cannot be rejected. Table 6 gives the statistics for both rounds.

The table shows that the participants, in general, presented a better performance in the second round. Although there is no significant difference, considering the relatively small significance value and the data from the table, it appears that the game indeed helps the subjects to increase their attention over time. The within-subjects contrast considering

Table 6: Statistics of all sessions for both rounds

Statistic	First Round	Second Round
Minimum	29.8	38.3
25% Percentile	45.5	46.3
Median	48.8	55.5
75% Percentile	56.9	63.4
Maximum	79.0	73.4
Mean	51.2	55.7
Std. Deviation	10.5	9.62

each consecutive session shows that there is a linear trend on time, $F(1, 7) = 12.0$, $p = .010$, $\eta_p = 0.632$. This result indicates that the average performance of the subjects over the sessions can be predicted by a positive linear curve. Figure 14 shows the average scores for each session, scaled in the vertical axis.

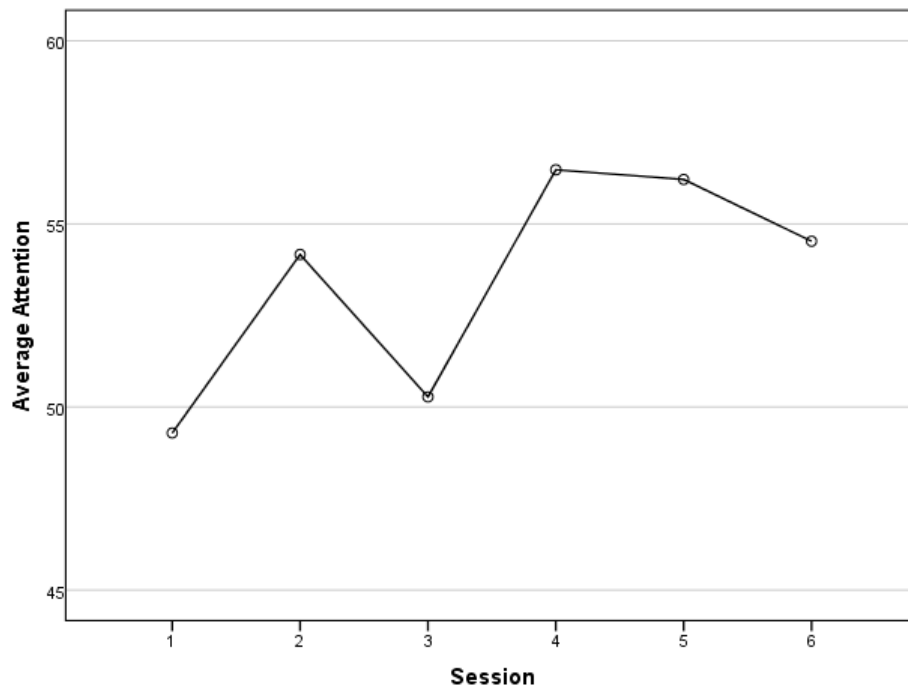


Figure 14: Average attention of the subjects in each difficulty

The average attentions of the matches of each difficulty level were also tested to check if there was a significant difference in the performance depending on the difficulty. A repeated-measures two-way ANOVA test was applied considering the matches of each subject on both rounds, in order to include possible main effects of time. The IVs are the time, with two levels (first and second round), and the difficulty, with three levels (easy, medium and hard). The test shows that there is no significant main effect of difficulty, $F(2, 21) = 0.234$, $p = .794$, i.e., it appears that facing a tougher opponent does not impact

the subject's attention. Also, there is no main effect of time (although there is a trend to a significant difference), $F(1, 21) = 3.77$, $p = .066$, and no significant main effect of the time vs. difficulty interaction, $F(2, 21) = 0.413$, $p = .667$. This indicates that any variation in time is the same for all the three difficulties. Figure 15 presents the average attention for each game difficulty before (first round) and after (second round).

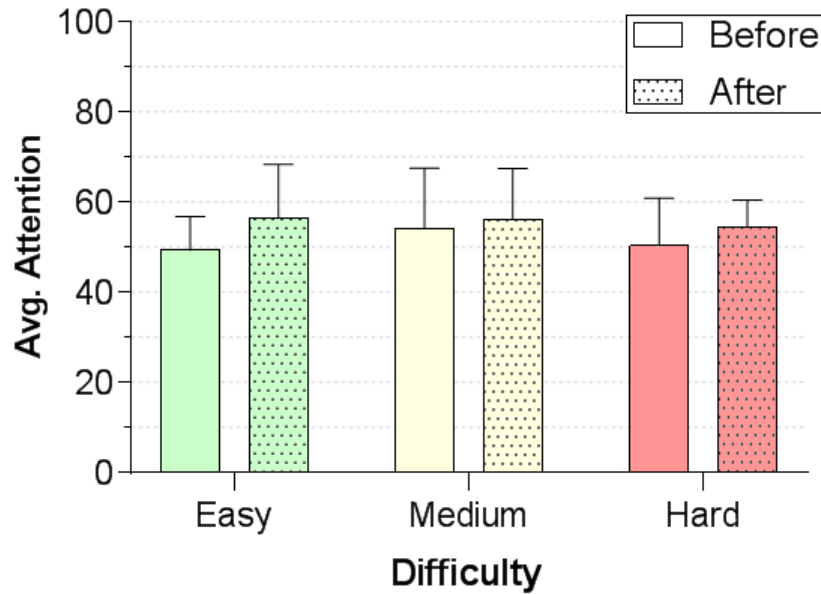


Figure 15: Performance of the subjects in each difficulty.

4.2.2 RQ2: Does the game's graphical user interface affect the average level of attention of the users?

To check whether there is a significant difference between the average attentions of the matches with and without GGUI, a repeated measures two-way ANOVA was applied by grouping the matches with and without GGUI into separated groups. As there are two matches of each game mode per session, their average was considered the score of that mode, thus totalizing one value per subject for each session, one for each game mode. Therefore, there were a total of 12 values per subject. The IVs, in this case, are time, with six levels (first to sixth session), and the game condition, with two levels (with and without GGUI). Mauchly's test for sphericity test shows that there has been no violation of the sphericity condition, $W = 0.187$, $X^2(14) = 20.260$, $p = .129$, so the F-value for the main effect of time and its interaction with the between-group variable does not need to be corrected. Also, Levene's test for equality of variances was also non-significant for all groups.

For the within-subjects condition, the result shows that there is no main effect of

time, $F(5, 70) = 1.01$, $p = .419$. This result suggests that there is no effect of time for both groups. Also, there is no significant main effect of the time vs. condition interaction, $F(5, 70) = 0.469$, $p = .798$. This suggests that both groups changes equally in time. Finally, there was also no significant main effect of the between-subjects condition, $F(1, 14) = 1055$, $p = .962$. This means that we cannot reject the null hypothesis, i.e., there is no significant difference in the average attention of the subject in the matches with and without GGUI. In fact, the p-value was so high that one can state that there are virtually no differences in performance for the matches with and without GGUI. Figure 16 shows the average attention for each session of each group separately, scaled in the vertical axis.

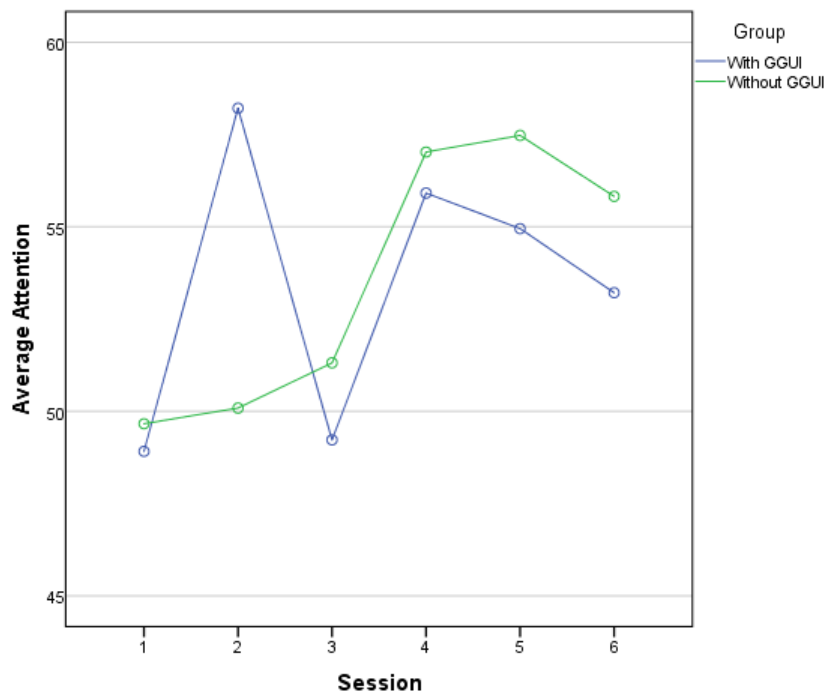


Figure 16: Average attention of each game mode per session

The Pearson coefficient was calculated to find the correlation between the average match duration and the average attention of each subject (i.e., the average of all attention data of each subject and the average of the duration of all matches of each subject). A value of .5238 was found, indicating that there is a moderate positive correlation of these two variables, i.e., there is a tendency to a longer match duration the higher is the subject's attention. This is somewhat expected due to the logic of the difficulties of the game: to defeat more challenging matches, the subject has to keep his average attention high for a longer period of time. If his attention is low, the match will last close to the minimum match duration, especially in the hard difficulty setting.

There was also no difference in the average time of the subjects in each game mode.

Figure 17 shows the total time spent by the subjects in each game mode. It can be noticed that the time for each mode can be very different for a particular subject (S3 and S7 spent more time in the matches with GGUI, while S8 spent more in the matches without GGUI), or be nearly equal for others (S1, S2, S4, S5 and S6 had spent similar times in each mode).

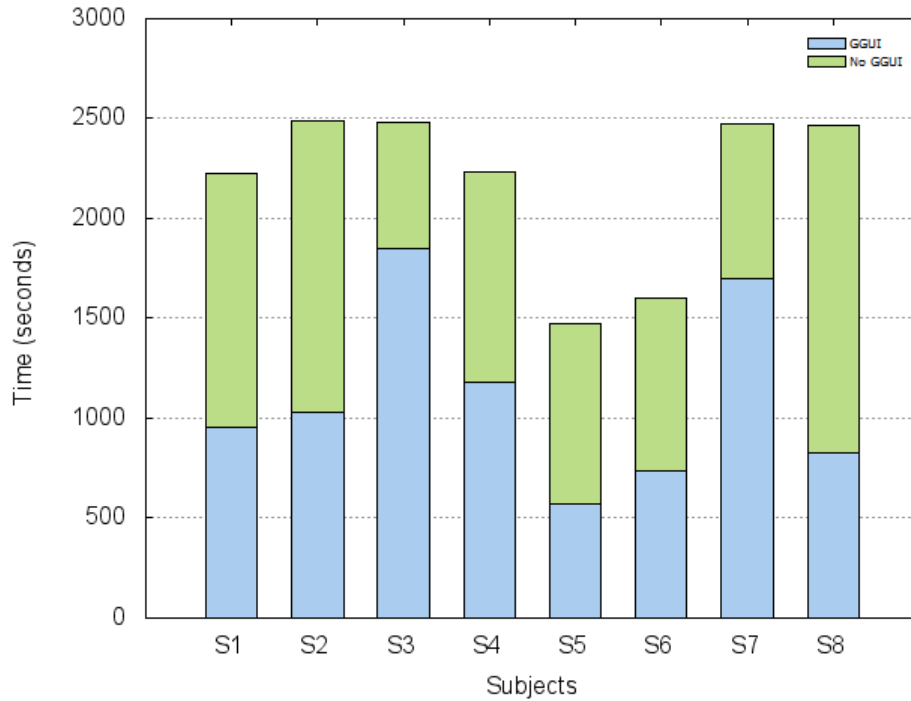


Figure 17: Total time spent in each configuration by each subject

4.2.3 RQ3: How do the subjects perceive their attention-based control over the game?

As stated in the methodology process, after every pair of matches in a game mode (with or without GGUI), a SAM formulary was assigned to the participant. The boxplots in Figure 18 shows the average self-assessed values for all subjects over the 24 matches of each one, with a total of 12 values (one SAM per two matches) per subject in each game mode.

A t-test was applied with the control values for the matches of each game mode (with and without GGUI) and of each round, but no significant difference was found (p-values of .5373 and .3297, respectively). The other states had also not shown a significant difference in either tests. To analyze the affective quality of the subjects' interaction with the game, the method proposed by Hayashi et al. (2008) was adopted. The data of the three states of the SAM forms were divided into three groups: Negative Ratings (R-), Neutral Ratings

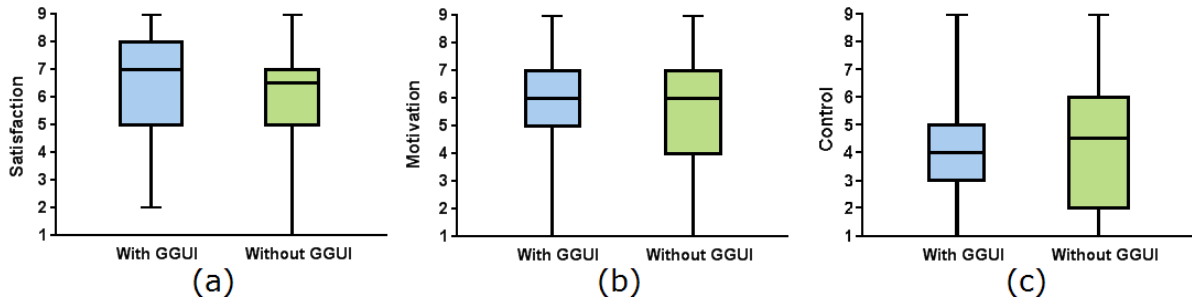


Figure 18: Average (a) Satisfaction (b) Motivation and (c) Control for each configuration

(RN), and Positive Ratings (R^+). Table 7 shows the summarized result, and Fig. 19 presents the distribution of the SAM values in each group.

Table 7: SAM values distribution in each group

Rate	Satisfaction	Motivation	Control
R^+	58	59	25
RN	24	15	22
R^-	14	20	51

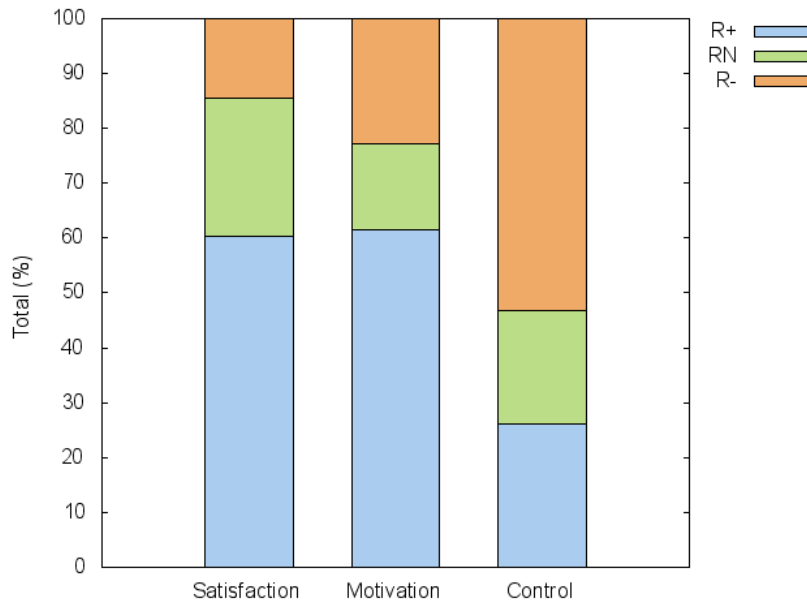


Figure 19: SAM ratings distribution

The distribution indicates that the subjects, in a general sense, enjoyed the game and were motivated to play it, as the majority of satisfaction and motivation values were positive, while the control values were mostly negative. Players with better results in the matches, i.e. who have defeated the computer or presented high average attention, in general reported a higher rating to satisfaction and motivation, but not in control. It

appears that, even when having a better performance, the subjects did not felt in control of their attention.

Complementing the SAM instrument, the videos of each session were also analyzed to access extra qualitative data from the experiment, such as details of how the subjects played the game and the detailed answers of the interviews.

Regarding the strategies that the participants employed to play the game, at first the majority of the subjects tried to just keep visual contact with any of the elements in the screen, such as the avatars, the focus bar or a single pixel. However, they experimented with many other strategies to try to find what best fitted for them. The most common strategies used in the matches with GGUI were to mentally focus on moving some object in the game, e.g. pulling the avatar or pushing up the focus bar; trying to remember a music or a video with details; doing mathematical operations; and trying not to think in anything. Many subjects (S1, S2, S4, S5, S6 and S8) tried to concentrate by closing their eyes, but every attempt to do so resulted in an instant loss of attention, and few subjects tried it more than once. The strategy that gave the best results was first employed by S4 (also the subject with highest performance) in the second session, and consisted in trying to make the focus bar go down, instead of up. The idea behind this method, as the subject explained, is that when trying to make the bar go up and it goes down instead, the player loses focus because he/she gets nervous. By trying to make it go down, the player does not lose focus when it actually descends, as he/she is achieving the desired result. If it goes up, focusing on trying to bring it down again will actually increase the subject attention, keeping the average high enough to win the game, without making the subject nervous.

For the matches without GGUI, as there were no objects on the screen besides the red dot in the center, some subjects (S5, S6, S7 and S8) tried to focus on making this dot change its color or to move it, while others just kept the same strategy used in the matches with GGUI, trying to keep visual contact with the dot. Some subjects tried methods to increase the concentration on the dot. Participant S6, for example, tried to look to the dot “through” his finger, by keeping it in front of his eyes, as shown in Figure 20. Other subjects (e.g. S2, S5 and S8) tried to look away from the screen and focus on some object in the room, such as a light source or a button. There was no noticeable difference in the attention in both cases; however, in the cases when the subjects closed their eyes to try to increase their concentration, a noticeable decrease in the attention was perceived. No subject tried to close their eyes as a control strategy after the first attempt.



Figure 20: Subject using his finger to concentrate

In relation to the preference for the matches with or without GGUI, the subjects' opinions were divided. As stated before, part of the subjects preferred the matches with GGUI, part preferred without GGUI and some switched opinions from the first round to the second. For the subjects who preferred the matches with GGUI (S1, S2, and S8), the main argument was that the lack of visual elements makes the game boring and appearing to last longer. Also, as there is no feedback from the game, the subject does not know if he is winning or losing, and if the adopted strategy is working or not. As S8 stated: *"As I do not know whether am I winning or losing, to wonder what is happening in the game makes me lose focus. Sometimes, when the game is taking too long, I think that I am losing and that I should give up; but, I can also be very close to win the game, so it motivates me to keep going. The lack of feedback makes me more agitated and wanting the game to end faster."* Participant S2 had a similar opinion: *"I think that without the GGUI, I get tired faster as I do not know what is happening in the game. Even if I concentrate more, the tiredness takes my concentration away as the game progresses."*

As for the subjects who preferred the matches without GGUI, the opinions were centered in the fact that the animated elements often distracted the players. S7 stated that *"the (animated) objects draw my attention when I am more concentrated, especially when I am losing and the computer is pulling my character. When there are no animations, I feel more concentrated because I focus only in the red dot. However, the animations make the game itself more attractive, and I think that there should be more animations and some music, despite the distractions."* Participant S5 stated: *"I always feel that the game is easier without the GGUI, as there are no distractions, the characters are not moving, and I do not get to keep changing my visual focus as I would do with the GGUI. When I see that I am losing, I always try to change my focus to another object on the scene,*

and this decreases my performance. I also always want to know what is happening to my character, so it is harder to concentrate.”

4.3 Related Works

A number of experiments and evaluations using BCI-based applications were performed to investigate the interaction of the users with the BCI platform, evaluating their performance according to the visual feedback or the training provided.

In the work of McFarland, McCane and Wolpaw (1998), an experiment was conducted to verify the short-term effects of visual feedback in the users’ performance on EEG control, specifically on the control of mu rhythms. The experiment had ten subjects and has shown that, at least in short-term, the EEG control is not dependent on the visual feedback, but it can have positive or negative influence on the performance, varying depending on the subject. Although the removal of the visual element had not significantly changed the overall performance of the population, the performance from the trials without the feedback was not correlated to the ones with the feedback for some users.

Pineda et al. (2003) also investigates the control of brain rhythms, but using a rich visual representation of the signal feedback. Four subjects were trained for ten hours over five weeks to be able to control mu rhythms. It was shown that the subjects learned to control the brain rhythm very quickly using realistic, interactive and motivationally engaging tasks, such, in this case, a 3-Dimensional first-person shooter game. In this game, the participants were able to control the front-back movement of the character using the keyboard and the left-right movement using the mu rhythm. It was also argued that the lack of control in some of the tasks may be related to distractions provided by the visual feedback to the users.

Kauhanen et al. (2006) conducted a short experiment for comparing the visual and haptic feedbacks of a BCI-based application. In the experiment, six subjects were divided in two groups; the first group received haptic feedback in the first three sessions and visual feedback in the last three; the second group received the feedbacks in the opposite order. Using imagined movement, the subjects were to imagine either right or left hand movement depending on the feedback. The results showed that there was no significant difference in the performance of the subjects according to the different feedbacks, as subjects got better at using the BCI system regardless of the modality used.

The experiment conducted by Karamnejad et al. (2014) suggests that the visual feed-

back provided by highly abstract animations, rather than simple direct animations such as a transitioning image or a progress bar, helps to distribute the user's attention and increases his/her relaxation, as there is no focus to the users to direct their gaze at. On the other hand, the inverse can also be applied: simple direct animations representing the visual feedback might focus one's attention more intensively. Chen et al. (2012) investigated the relation between attention concentration and visual stimulation in an EEG control experiment. In the experiment ten subjects were divided in two groups, one presented with visual stimulation of a computer game and the other not. The results showed that the presentation of visual stimulus increased the power spectrum of both alpha and beta frequency ranges, thus indicating that there may be a positive correlation between visual stimulation and increased attention.

For the best of our knowledge, there are a very little number of researches that aims to evaluate the influence of the graphical user interface (thus the visual feedback) on an attention-based BCI computer game, specially using the NeuroSky MindWave headset.

4.4 Discussion

The results of the experiment are discussed based on (a) the research questions; (b) the related works; and (c) additional analysis on qualitative and quantitative aspects of the subjects' experience on the game. The limitations of the experiment and its results are also described.

4.4.1 Research Questions

By analyzing the results from the perspective of the research questions, it is interesting to notice how the qualitative results compare to the quantitative ones. In almost every session, the subjects reported to perceive their concentration higher or lower in a particular match of a specific game interface mode; however, the result of the match often shows the inverse: their attention was, in fact, higher or lower (usually lower) than what was perceived by the subject. It was noticed that the majority of the subjects, especially in the first sessions, had not a very solid concept of what kind of concentration was being measured by the headset. The initial explanation of the experiment had the objective of both introducing the subjects to the BCI system and the game, and to explain what specifically the headset was measuring, with examples of what would be to "concentrate" (e.g. to avoid diverging thoughts, keep focused visual contact with a fixed point etc.).

However, despite reporting that they understood all the explanation and that they had no doubts, in the interviews it became clear that the subjects had not fully understood the concept, as they frequently appeared to be confused with their performance not being what was expected.

As for the influence of the GGUI in the players' attention, a possible explanation for the visual and animated elements of the game screen to have not made difference in the subject's performance may be that the equipment used to acquire the players' attention receives data from a single electrode located at the Fp1 region (on the 10-20 international system). The Fp1 region acquires signals from the frontal lobe of the brain, which is associated with short-term memory tasks, motivation, planning and attention itself. As the visual cortex is located in the occipital lobe, it makes sense that the subject's attention, acquired in the frontal lobe, is not significantly influenced by the visual information received and processed in the occipital lobe, which is also responsible for processing movements in the vision. However, this result is limited to the context of the NeuroSky MindWave headset only, as other equipment, such as the Emotiv Epoc, may acquire signals from multiple regions at the same time and combine those information using a different algorithm.

The values for the Motivation and Control states had more variation in the matches without GGUI. This could be explained by the fact that a few subjects (S1, S3, and S4), in the first round, stated that they do not like to play the matches without the GGUI, as they did not know what was happening in the game, or if they were winning or losing; but, in the second round, they started to enjoy the matches without GGUI, or started to have doubts as whether it is easier or harder to play in those matches, as they realized that there was no animated elements to shift their attention, thus apparently increasing it. However, a few subjects (S2 and S8) preferred the matches with GGUI for the whole experiment.

The satisfaction state had an overall lower variance and mean in the matches without GGUI. As some subjects had stated, despite having the sensation of more concentration in those matches, as there were no graphical elements to draw their attention, the game starts to become monotonous after the first minutes. Subject S2 said: *"The game without BCI becomes tedious after a while. In the beginning of the match, I feel that I am concentrating more, but wishing to know what is happening on the game makes me lose my focus fast. I think that this negative effect overcomes the positive, especially if the game takes too long."*

Comparing the numerical results of the SAM control values obtained from the matches with and without GGUI to the statements of the subjects, it is interesting to notice that, despite the fact that many participants had perceived a better concentration and performance in the matches without GGUI, statistically there is no difference comparing to the matches with GGUI, as shown in the results of the quantitative data. The lack of graphical elements only caused the impression of greater performance and higher attention, but numerically and statistically it had no difference.

Additionally, regarding the sensation of control reported by the subjects using the SAM formularies and the interviews, the results show that the players felt that they were not in control of the game character itself. However, it is known that the subject experience in using BCI platforms may influence in this perception. In the study of Barbero and Grosse-Wentrup (2010), for example, in which a biased feedback was applied to inexperienced and experienced subjects in an imagined movement based BCI experiment, it was shown that accurate feedback in inexperienced subjects may be perceived as random noise, as it may not always correspond to the intended movement. The authors also conclude that, in such cases, a positive biased feedback may decrease this feeling of randomness, while it may decrease the performance of experienced subjects. Applying this result in the context of the Mental War game, it would be interesting to investigate whether a biased feedback based on the subjects' experience may positively influence its performance (e.g., positive biased feedback based on the easy difficulty game mode).

4.4.2 Related Work

The results from some of the related works seem to corroborate with the experiment data. In the work of Kauhanen et al. (2006), for example, the change in the provided BCI feedback had no difference in the performance of the players. In the experiment of Karamnejad et al. (2014), the attention of the subjects was distributed, rather than focused, and an increase in their relaxation was noticed. Comparing to the Mental War game, in which the visual elements could possibly distribute the player's attention, no difference was found in relation to the case with focused attention, i.e. without the GGUI. However, the relaxation data of the subjects was not evaluated in our experiment.

The results shown by McFarland, McCane and Wolpaw (1998) suggest that, for some users, the data from the cases with the visual feedback does not correlate with the ones without the feedback. This is partially true in the case of the Mental War experiment. In general, considering the overall population of the experiment, no statistically significant

difference is found comparing the performance with or without GGUI. However, considering subjects individually, there is also no significant difference considering the matches of both cases. It is important to notice, however, that the design of the experiment may have influence in this scenario, as each subject played matches of both with and without GGUI in the same session.

The improvement of the subjects' performance in the second round of sessions is in accordance with other researches in the field. Dekker et al. (2014), for example, investigated the training of 18 subjects on the course of 15 sessions of alpha feedback training, and the effects were discussed in terms of attention and motivation of the subjects. The research showed that after 10 sessions, the alpha power, related to internal attention, increased and remained for the following five sessions. In the work of Thomas, Vinod and Guan (2013b), the impact of neurofeedback in a BCI game was analyzed in a five days experiment with eight subjects, and it was shown that the performance of all players increased throughout the sessions. These results show that games like Mental War can indeed help the players to increase their focused attention over time.

4.4.3 Additional Analysis

The experiment brought many insights regarding the development of BCI-enabled games. With the analysis of the videos and the statements made by the participants, it is clear that a time limitation for the matches would increase the user experience with the game. Many subjects complained that some matches took a very long time to finish, especially in the matches without GGUI, and suggested that there was a time limit for the duration of the match. Being a game that requires the player to stay mentally focused for a relatively long period of time, it is no surprise that the average attention generally decreases over the course of the match and over the four matches of the day.

Another issue that was addressed by the subjects was the difficulty of the matches. For some subjects (particularly S1, S2, S3 and S8), the game is particularly hard even in the easy difficulty setting. The computer has an average attention of 55 in the easy setting, which is in the "default" levels of 40 to 60 attention that an awake person has in normal conditions, according to the NeuroSky MindWave user guide (NEUROSKY, 2011). This difficulty may be related to the fact that no subject had any experience with BCI-based games, nor with focused control of their attention. Anxiety and hyperactivity disorders could also explain the overall difficulty that some subjects had throughout the matches, but no subject has been officially diagnosed with such disorders. Some subjects (S1, S5,

S7 and S8) had also mentioned that the “Medium” and “Hard” settings are too fast, as the computer already starts with a high attention level that is maintained through the match, while the subject still has to concentrate for a few seconds to reach this attention, and in the meanwhile the computer has already pulled his avatar closer to the center. According to a research conducted by Crowley et al. (2011), the higher is the level of attention of a subject, the higher is his/her level of stress, and as the difficulty of a task increases, subjects seems to lose interest and reduce their level of attention, thus decreasing their stress level. That result is in accordance to the behavior shown by the subjects in this experiment. A possible solution proposed by a few subjects was that the computer started with a lower attention level that progressively increases towards the current value.

Yet another reason for the players’ difficulty in maintaining a high attention may be the fact that, when losing a match, they get frustrated and tries a different playing strategy. The great majority of the subjects (S1, S2, S3, S5, S6 and S7) switched between focusing on a fixed position on the screen, trying to move some object, or remembering songs, even in the middle of an ongoing match. As the player do not train the same strategy for a series of matches, it is possible that he/she does not gain as much experience as a player that maintains the same strategy over many sessions.

Many subjects had some kind of problem with the headset in at least one of the sessions, but the majority was just poor signal received from the headset due to some interference or its bad adjustment on the head. The headset signal status icon changes to yellow when there is a small number of interference, and usually return to normal on its own after a few seconds. In the few cases where the icon took too long to return to normal or when the status icon turned to red (due to misplacement of the electrode sensor on the forehead), the headset was adjusted and the match was restarted. This event occurred only three times and with different subjects: S2, S6 and S8. Only one participant (S8), however, had stated that the headset was causing discomfort, as the right rubber part of the headset keeps pressure on the right temple, to maintain its position on the head. This particular subject also stated that, after longer sessions, the discomfort was greater as he/she has high pressure on the right eye. However, based on the analysis of the videos, it can be noticed that most part of the subjects wanted to remove the headset as soon as the last match was over, with signs of discomfort and relief. Shorter sessions and matches could possibly reduce this discomfort, as the subject would have to spend less time wearing the headset.

4.4.4 Limitations

There had been cases of subjects reporting to be feeling tired, hungry, stressed, or having had a poor night of sleep. Any possible influence of lack of sleep, tiredness, and cerebral hematic changes due to food or hormonal factors are beyond the control of the researchers. Also, the sample size (eight subjects) may be considered small for a comparative study. In future studies, it would be interesting to have a bigger sample size and with a larger variance in their age, as the majority of the subjects were young adults. It is not known, for example, if these results hold for children and elders.

As the algorithm used by the BCI EEG equipment is unknown, a calibration match occurred at the beginning of each session in order to avoid any accuracy issue related to a possible learning feature of the headset. However, even if the result of this match is excluded from the evaluation of the experiments, its occurrence may have influenced the results of the following matches, as the subject gathers more experience and it may increase his/her fatigue. This is important to highlight, especially in this experiment, as some calibration matches had long durations. To avoid this issue in future experiments, a fixed-duration match could be employed.

The experiment protocol adopted in the first experiment is based on five matches per session (including the calibration match), but alternating between matches with and without GGUI. The effects of this change in every session is unknown and may have influenced the results; however, a counter-balance was applied in the second round, i.e. the order was inverted, in order to minimize any possible effect. To avoid the influence of confounding results in future studies, a between-subject design may be used instead, i.e., two groups of subjects, each assigned to one interface configuration.

The games have a fixed set of animations and sounds, which had not influenced, according to the results, the performance of the subjects. However, it is not known whether a different set or the addition of more animations and sounds could influence this result. Also, in the case of this experiment, the icons representing the status of the headset (i.e. if it is connected and the intensity of its signal) is displayed even in the matches without the GGUI. Changes in those statuses during the game may have distracted some of the subjects.

To minimize the effects of subject fatigue during the experiment, it would be prudent to conduct shorter sessions (e.g. three matches instead of five per session). Also, the sessions were planned to occur in sequential days for each subject, but some sessions had

a longer interval between each other. The effects of these intervals in the performance are unknown. The subject with the longest intervals between sessions was S8 in the first experiment, with a few less than 14 days of difference from the first session to the second, and nearly one month of interval from the second to the other four sessions. This delay was justified by the subject becoming sick for a long period and not being able to attend to the sessions for this time period.

5 The Influence of Auditory Stimuli on Users' Meditation and Workload:

In this chapter, an experiment using a meditation-based BCI game is described. This experiment, similarly to the first, is aimed at analyzing both qualitative and quantitative aspects of the subjects' interaction with the BCI platform and the game itself, but focusing on the influence of the auditory stimuli on the player's meditation. We also aim to analyze how the users perceive their self-assessed workload with the game and whether their performance changes over time. Based on these objectives, this experiment is guided by the following Research Questions (**RQs**):

- **RQ1:** Does the average level of meditation of the subjects changes over time?
- **RQ2:** Does the game's auditory stimuli affect the average level of meditation of the subjects?
- **RQ3:** Does the subjects' self-assessed workload changes over time?
- **RQ4:** Does the game's auditory stimuli affect the self-assessed workload of the subjects?

As with the graphical elements, the comprehension of the effects that the auditory elements have in neurofeedback-based games may help understand how the brain processes this feedback and how it influences the performance of the player, and may serve as guidance to BCI developers, researchers and game designers for future applications.

5.1 Methodology

This experiment was designed to evaluate specific aspects of the interaction of the players with a BCI game, especially those which could have influenced the average meditation

value during the matches, such as the presence of auditory stimuli. This section describes the methodology employed to perform the experiment.

5.1.1 Meditation-based BCI game

Zen Cat is an open-source BCI-based computer game, which was developed to be played with a NeuroSky Mindwave headset. In the game, the player controls a cat that must meditate in order to levitate and reach the highest height as possible. To achieve that goal, the player must also meditate, i.e., must maintain his/her average meditation eSense above a certain threshold. If his/her average meditation falls below the threshold, which is defined by the current height of the player, the cat starts to wake from his meditative state and stops levitating. The MindWave device sends a meditation value every second, but the game only uses the last 20 values to calculate the average meditation of the player, in order to allow for a greater variance in the averaged value.

Each match of the game has the exact same duration of two minutes. This relatively short duration for each match was imposed as a time limitation to avoid possible fatigue and tiredness from long sessions. The player score is calculated based on the highest height s/he achieved and the total average meditation (considering the values of the entire match).

The game interface is composed of four main elements: the headset status bar, which indicates the current status of the headset, such as whether it is connected, the battery charge and the signal strength; the height indicator, which represents the current height of the user in relation to the total scenario's height; a clock, which indicates the remaining time to the end of the match; and a meditation bar, which shows the current meditation threshold, the player's average meditation from the last 20 seconds and his/her current meditation. Figure 21 shows the game match interface.

The game can be played with or without sound (mute). The scenario is divided into five parts of equal size, and each part has a fixed set of animations. The game is configured to create a new animated element every four seconds, and each animation plays a sound when it enters the field of view of the player. This set of sounds and the option to play without sound were used to help answering the research questions, as stated and detailed below.

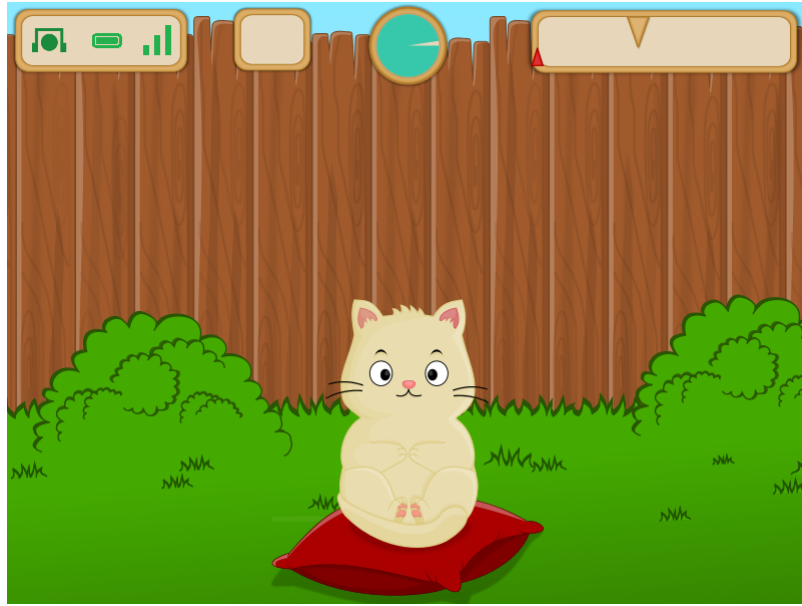


Figure 21: Zen Cat game match.

5.1.2 Research Questions

The RQ1 involves the investigation of whether the average meditation of the subjects changes over time, i.e., if the players learn to control their meditative state after playing the game multiple times; if their performance decreases instead, meaning that playing a game based on meditation did not accomplish its objective; or if the average meditation stays the same (the null hypothesis), meaning that playing the game multiple times causes no impact on the players' performance.

The RQ2, on the other hand, was elaborated to investigate whether there is a significant difference in the performance of the subjects playing with or without the Auditory Stimuli (AS). The aim is to compare the average meditation in both groups and verify whether there is a difference based on the presence of the AS, and investigate why this difference exists (or why it does not exist).

The RQ3 and RQ4 are similar to RQ1 and RQ2, respectively, but investigate the changes and differences in the workload instead of the average meditation. Both values are acquired from all subjects equally, so their processing and investigation are similar. The relation between the time and the groups is also investigated in regard to both the average meditation and the workload, in order to verify whether any change in the subjects' scores in relation to time occurs equally for both groups, with or without AS.

5.1.3 Participants

The experiment was conducted with sixteen volunteer subjects (S1–S16), being fourteen male and two female. Participants ranged from 22 to 35 years ($M = 24.94$, $SD = 3.61$). The only adopted selection criteria was that the participants had no metal plate implants in the region of the forehead.

5.1.4 Ambient and Materials

The same computer was used by all subjects for all sessions of the experiment. The experiment was conducted in a closed and climatized room. The computer is equipped with an Intel Core 2 Duo processor, 4 GB RAM, Windows 7 64-bits operational system and a 15" monitor, adjusted to the subjects' height.

All sessions were recorded with the participants' consent, using two Microsoft LifeCam Cinema cameras, both connected to another computer in order to avoid any possible performance loss in the game. The headset employed to acquire the subjects' brain signals was a NeuroSky MindWave model MW001.

5.1.5 Procedure

Each subject had to participate in three individual sessions of the experiment. Every session was recorded with the digital cameras. In the first session, the subject filled out a demographic form and the researcher explained the experiment. The subject was free to ask any question at any time, and watched one video that shows how the game works and how it is played with the EEG device.

In each session, four matches were played, being the first one only for the calibration of the headset and for the subject to prepare for the following three; these first matches were excluded from the analysis. Each participant played, therefore, a total of 12 matches. The 16 subjects were divided into two groups of eight participants: one group played the game with all sounds, while the other group played the game without any sound (mute). To assure internal validity, the subjects were randomly assigned to each group. Each subject could only participate in one session per day, to minimize any possible influence of tiredness or emotional state in the subject's performance over the course of many sessions.

At the end of each session, the player was asked to answer a NASA Task Load Index (

TLX) (HART, 1988) form in order to assess his/her subjective workload from the last three matches. The workload is a usability component and can be measured through specific questionnaires. The TLX uses six items to assess mental demand, physical demand, temporal demand, effort, performance and frustration. Each item is represented by a bipolar scale divided by 20 steps of five points each, resulting in a value that ranges from zero to 100. The subjective workload is calculated by the average of the values from the six items and the higher the resulting value, the higher is the task's subjective workload.

After each match, a short semi-structured interview was conducted with the participant to acquire relevant information about the match, such as what strategy he used to play, if he felt tired or fatigued, whether he found the match to be difficult, and general observations that emerged during the match. These interviews were used to assure that the subject would give more precise answers, as he had played the match just moments before.

5.1.6 Design

The experiment has, in short, a 2x3 mixed design, as each user is assigned to a group and each group tested for only one task (between-subject), but both groups were tested three times (within-subject). The independent variables (IV) are:

- The presence of AS (i.e. sounds), with two levels (with AS and without AS);
- The time, with three with three levels (first session, second session and third session).

The dependent variables were the average meditation of the participant and his/her self-assessment workload, both acquired at the end of each session.

5.2 Results

The results were divided and presented according to each research question separately. The quantitative results were obtained by applying a number of statistical analyses on the dependent variables, i.e., the output of the matches: the subject's average level of meditation and the self-assessed TLX workload. A D'Agostino & Pearson normality test was applied to guarantee the normal distribution of the values in all statistical analyses.

As there are two main factors that may affect the subjects' average meditation and the workload (i.e. the time and the presence of auditory stimuli), a repeated measures

between-within subjects MANOVA was conducted to verify whether any change in both the subjects' average meditation and in the workload was a result of the interaction between the presence of auditory stimuli and time. To address RQ1 and RQ2, the average meditation of the subjects in each session was considered, i.e., the average between the scores in the first (M1), second (M2) and third (M3) matches in each session (S): $S = (M1 + M2 + M3)/3$. Also, for each research question, follow-up tests were performed to analyze with more depth how the factors affected the dependent variables.

For the MANOVA test, the first IV is 'time', which has three levels: first session, second session and third session; and the second IV is the 'condition', with two levels: with AS and without AS. The DVs are the average meditation, i.e. a number that ranges from 1 (more stressed) to 100 (more relaxed), and the workload, also a number that ranges from 0 (minimum workload) to 100 (maximum workload).

Mauchly's sphericity test for the repeated measures is shown in Table 8. The main effect of time (sessions) did not significantly violated the sphericity assumption in both measures, as the significance value is greater than 0.05 for the average meditation, $W = 0.981$, $X^2(2) = 0.244$, $p = .885$, and the workload, $W = 0.741$, $X^2(2) = 3.899$, $p = .142$. Therefore, the F-value for the main effect of time and its interaction with the between-group variables does not need to be corrected for violations of sphericity. Levene's test for equality of variances was also non-significant, so the degrees of freedom does not need to be corrected either.

Table 8: Mauchly's test for sphericity.

Effect	Measure	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon		
						Greenhouse-Geisser	Huynh-Feldt	Lower-Bound
Time	Meditation	0.981	0.244	2	.855	0.982	1.000	0.500
	Workload	0.741	3.899	2	.142	0.794	0.943	0.500

For the within-subjects effect on the average meditation, the test revealed that there is no significant main effect of time, $F(2, 28) = 2.88$, $p = .073$. This result indicates that if the AS condition is ignored, there is no evidence that time is a significant predictor of the average meditation of the subjects. The test also shows that there is no significant main effect of the AS condition, $F(1, 14) = 1.94$, $p = .186$. This indicates that if the time factor is ignored, there is no evidence for a significant difference in the average meditation as a result of the presence of AS, i.e., the auditory stimuli are also not a significant predictor for the average meditation of the subjects. For the effects on the workload, there is also no significant main effect of time, $F(2, 28) = 1.88$, $p = .172$, and no significant effect of

the condition, $F(1, 14) = 0.895$, $p = .360$.

Finally, the test show that, when combining both factors, there is still no significant difference in the subjects' average meditation, $F(2, 28) = 0.41$, $p = .668$, nor in the workload, $F(2, 28) = 0.58$, $p = .568$. This result suggests that there were no influence on the scores due to the interaction of the mixed between-within effect (condition vs. time), i.e., any effect of time in the dependent variables applies equally in both groups.

5.2.1 RQ1: Does the average level of meditation of the subjects changes over time?

Based only on the results of the mixed MANOVA, there is no evidence of a significant effect of time on the subjects' average attention. However, there is indeed a difference in the mean average of meditation when comparing the individual sessions. Table 9 gives the statistics for all three sessions.

Table 9: Statistics of average meditation from all sessions.

Statistic	First Session	Second Session	Third Session
Minimum	45.1	44.8	49.0
25% Percentile	52.0	56.9	59.1
Median	56.6	64.8	64.3
75% Percentile	59.5	66.4	68.1
Maximum	71.9	76.0	72.4
Mean	57.3	61.6	63.0
Std. Deviation	6.82	8.40	7.03

The Table 9 shows that the participants, in general, presented a better performance in the second session in comparison to the first, and in the third session in comparison to the two previous. A trend analysis on time revealed statistically significant results in the within-subjects contrast with the average meditation, $F(1, 14) = 4.88$, $p = .044$, $\eta_p = 0.258$. This result suggests that there is a linear trend of the average meditation in relation to time, i.e., that the game may indeed help the subjects to increase their meditation over time, regardless of the AS condition. No significant trend was found in the time vs. condition relation, $F(1, 14) = 0.63$, $p = .442$. Figure 22 presents the average meditation per match of all subjects from both groups. The statistics for each match (M1, M2 and M3 as the first, second and third match, respectively) of each session is presented in Table 10.

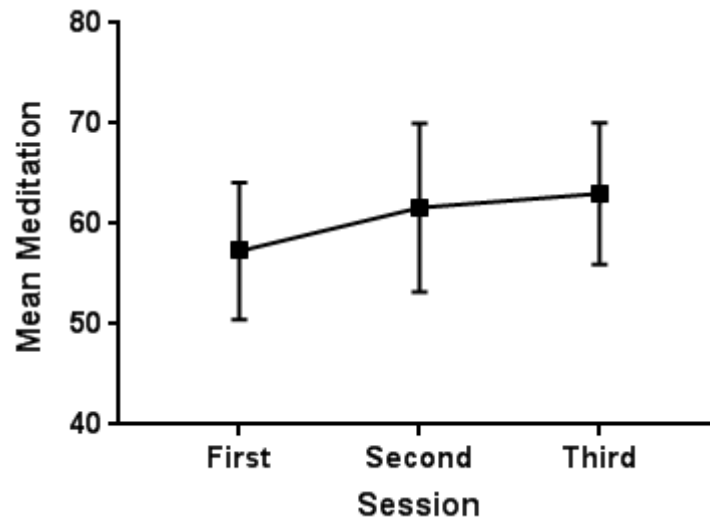


Figure 22: Average meditation per session.

Table 10: Statistics of average meditation for all matches of all sessions

Statistic	First Session			Second Session			Third Session		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
Minimum	33.1	42.5	37.8	36.0	43.4	45.1	45.9	45.7	51.7
25% Percentile	53.6	50.4	49.0	57.8	52.7	55.5	59.1	54.2	59.5
Median	61.3	54.6	59.3	64.8	62.3	61.0	68.0	60.6	63.1
75% Percentile	69.2	58.9	65.0	72.3	67.3	64.8	71.3	64.9	67.62
Maximum	76.0	74.8	69.2	85.3	79.5	69.3	79.7	82.2	75.9
Mean	59.3	55.5	57.1	63.6	60.8	60.4	65.0	60.8	63.3
Std. Deviation	12.0	8.11	9.61	12.5	10.9	6.51	9.72	8.87	6.95

5.2.2 RQ2: Does the game's auditory stimuli affect the average level of meditation of the subjects?

While considering the main effect of the AS condition alone, the results of the MA-NOVA suggest that there is no statistical significant difference from both groups, with and without AS. Figure 23 presents the average meditation for both groups on all three sessions.

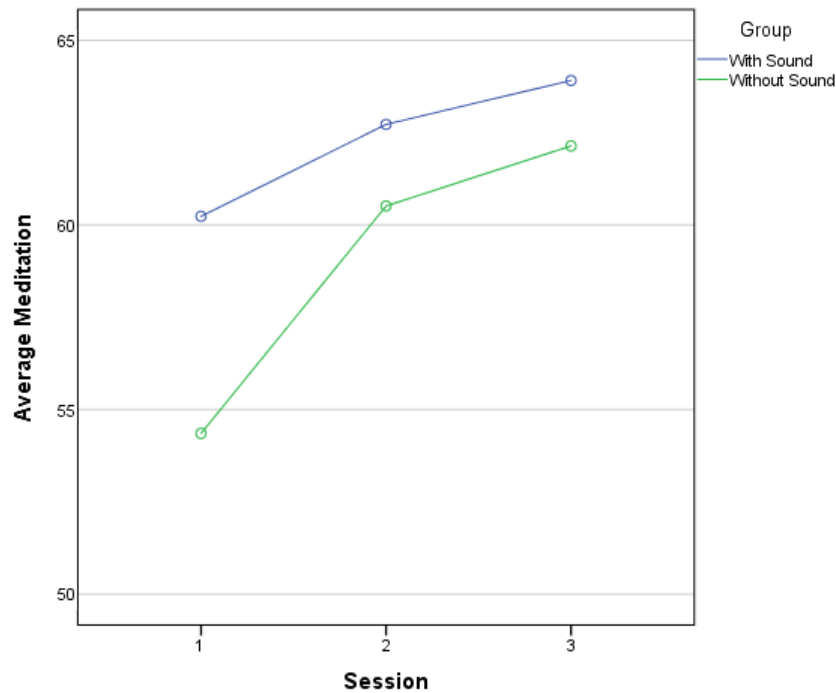


Figure 23: Average meditation per session from both groups.

Although the average meditation from both groups increases over time, the scores for the group without the AS is lower in all three sessions in comparison to the group with AS. However, there is no statistical evidence that this effect happened due to the presence of AS. The increased scores in relation to time is in accordance with the trend analysis and the non-significant relation of group vs. time, i.e., the average meditation tends to increase with time, but this increase is likely to occur in both groups equally. Table 11 presents the statistics of average meditation for both groups, while the boxplots in Figure 24 shows the statistics of the average meditation for both groups.

Table 11: Statistics of average meditation for all sessions from both groups

Statistic	With Auditory Stimuli			Without Auditory Stimuli		
	Session 1	Session 2	Session 3	Session 1	Session 2	Session 3
Minimum	51.8	44.8	56.0	45.0	48.9	49.0
25% Percentile	56.9	63.1	60.9	51.5	53.6	57.1
Median	58.9	65.5	63.8	53.3	60.6	64.3
75% Percentile	61.5	66.4	67.3	57.1	65.7	68.4
Maximum	71.9	69.4	72.4	63.9	76.0	72.4
Mean	60.2	62.7	63.9	54.4	60.5	62.1
Std. Deviation	6.72	7.84	5.43	5.90	9.32	8.64

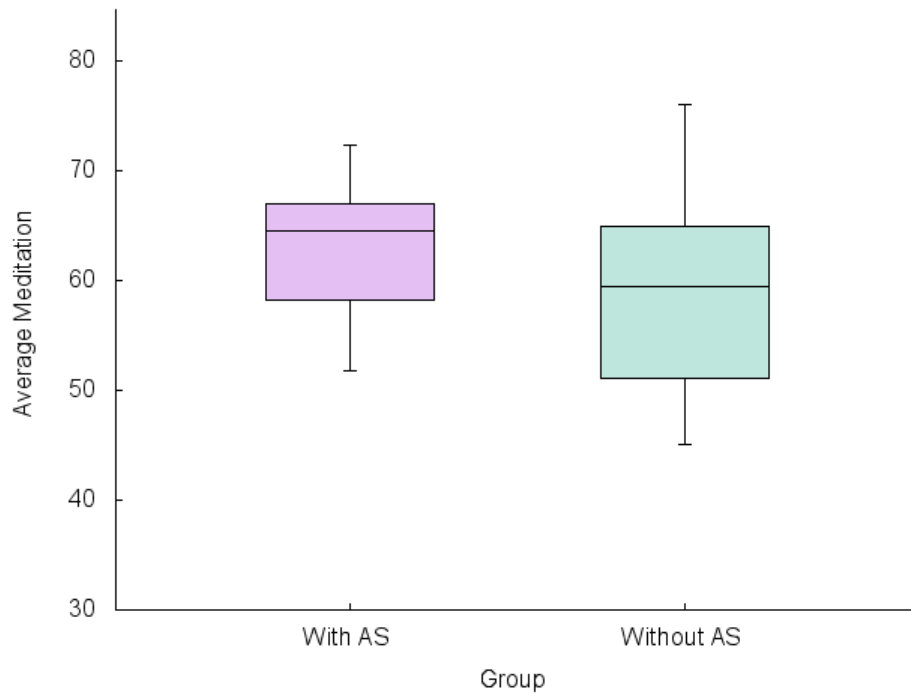


Figure 24: Boxplots of average meditation per group.

5.2.3 RQ3: Does the subjects' self-assessed workload changes over time?

As stated in the methodology process, after every session of three matches, a TLX form was assigned to the participant. Based on the results of the MANOVA, similarly to the average meditation, there is no clear evidence that there is a main effect of time on the subjects' workload, but there is a difference in the mean score from the three sessions. The statistics for these workload values for all sessions are presented in Table 12.

Table 12: Workload statistics of all sessions.

Statistic	First Session	Second Session	Third Session
Minimum	19.2	15.8	15.0
25% Percentile	26.7	23.3	26.3
Median	40.0	32.9	30.4
75% Percentile	48.1	41.5	42.5
Maximum	61.7	63.3	47.5
Mean	39.0	33.6	32.6
Std. Deviation	14.0	13.0	10.4

The table shows that the mean workload decreases in the course of the sessions, especially from the first session to the second. A trend analysis on time also reveals a statistically significant result in the within-subjects contrast with the workload, $F(1, 14) =$

6.11, $p = .027$, $\eta_p = 0.304$. This result indicates that there is a linear trend of the mean workload in relation to time, i.e., that the subjects perceive a decreased workload while playing the game the more they play, regardless of the AS condition. As with the average meditation, no significant contrast was found in the time vs. condition relation, $F(1, 14) = 1.27$, $p = .279$. The boxplots in Figure 25 summarizes the self-assessed values for all subjects over the three sessions.

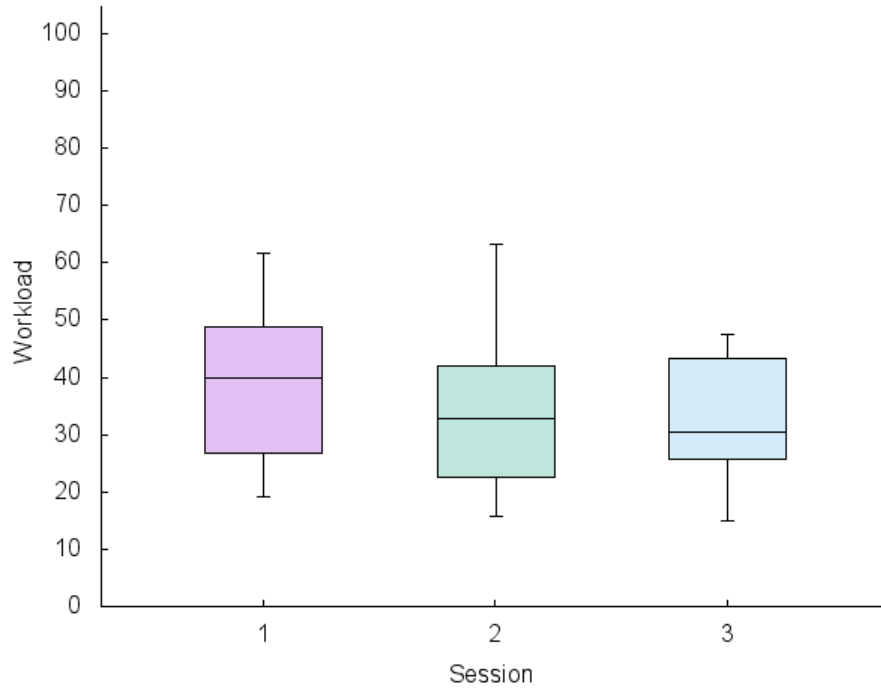


Figure 25: Boxplot of the self-assessed workload from the three sessions.

5.2.4 RQ4: Does the game's auditory stimuli affect the self-assessed workload of the subjects?

Similarly to the average meditation, the results show that, while considering the main effect of the AS condition alone, there is no statistical significant difference from both groups, with and without AS, in relation to the workload. Figure 26 presents the average workload for both groups on all three sessions.

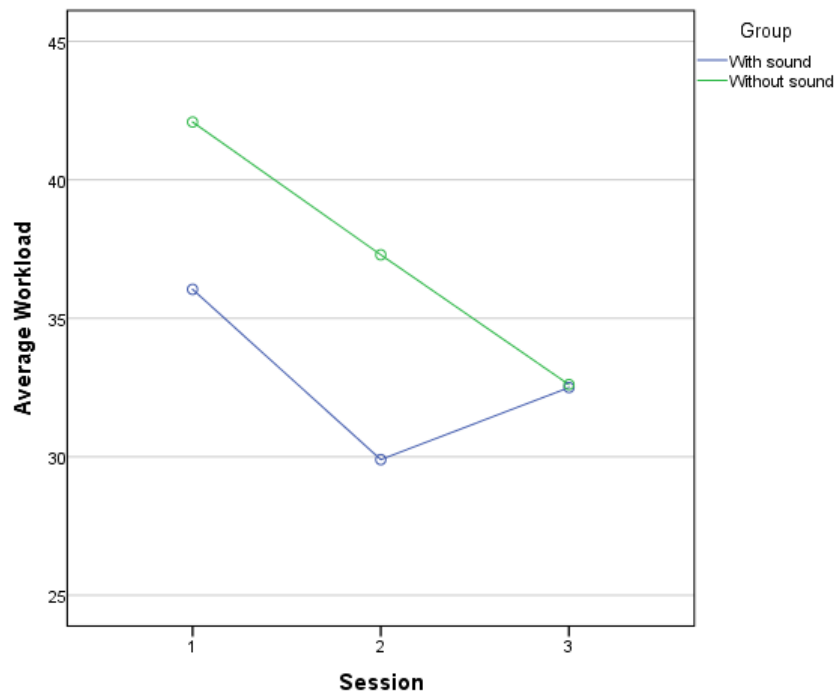


Figure 26: Average workload per session from both groups.

The average workload from both groups decreases over time, with the scores for the group without the AS being greater in all three sessions in comparison to the group with AS. However, there is also no statistical evidence that this effect happened due to the presence of AS. Also similarly to the tendency in the average meditation, the decreased scores in relation to time is in accordance with the trend analysis and the non-significant relation of group vs. time, i.e., the workload tends to decrease with time, but this decrease is likely to occur in both groups equally. Table 13 presents the statistics of workload for both groups, while the boxplots in Figure 27 summarizes this data.

Table 13: Statistics of workload for all sessions from both groups

Statistic	With Auditory Stimuli			Without Auditory Stimuli		
	Session 1	Session 2	Session 3	Session 1	Session 2	Session 3
Minimum	19.2	15.8	15.0	22.5	20.8	25.0
25% Percentile	29.0	19.8	22.3	26.7	26.7	27.3
Median	40.0	27.9	30.4	40.8	39.2	30.4
75% Percentile	42.9	39.0	46.9	58.5	41.5	36.0
Maximum	50.0	47.5	47.5	61.7	63.3	45.0
Mean	36.0	29.9	32.5	42.0	37.3	32.6
Std. Deviation	11.2	12.4	13.3	16.4	13.5	7.33

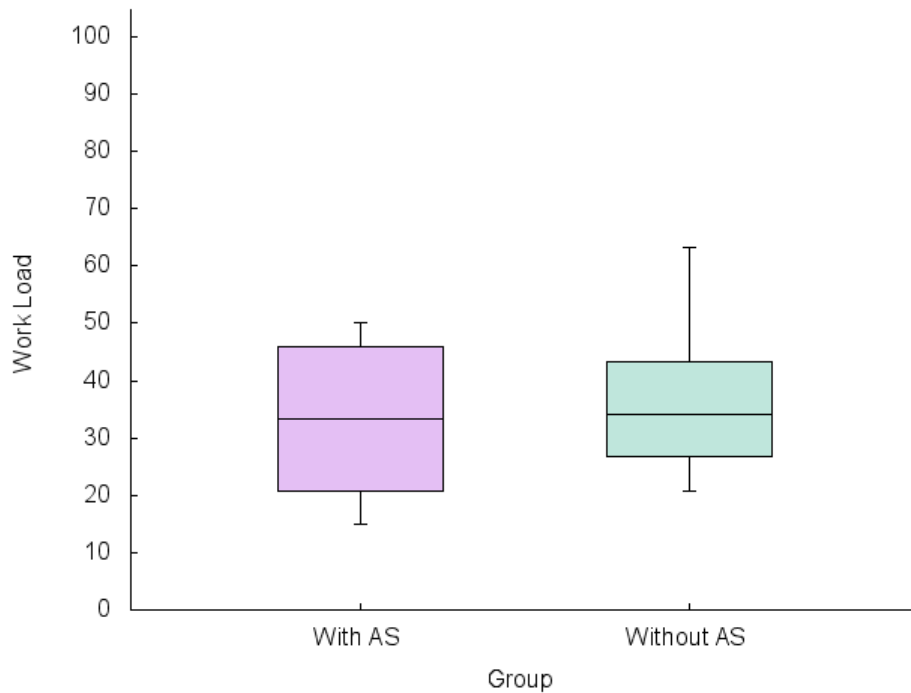


Figure 27: Boxplots of workload per group.

5.3 Limitations

As with the first experiment, there had been cases of subjects reporting to be feeling tired, hungry, stressed, or having had a poor night of sleep. Any possible influence of lack of sleep, tiredness, and cerebral hematic changes due to food or hormonal factors are beyond the control of the researchers. Also, the sample size (sixteen subjects) may be considered small for a comparative study. In future studies, it would be interesting to have a bigger sample size and with a larger variance in their age. It is not known, for example, if these results hold for children and elders.

Also similarly to the first experiment, as the algorithm used by the BCI EEG equipment is unknown, a calibration match occurred at the beginning of each session to avoid any accuracy issue related to a possible learning feature of the headset. However, even if the result of this match is excluded from the evaluation of the experiments, its occurrence may have influenced the results of the following matches, as the subject gathers more experience and it may increase his/her fatigue. In this experiment, this calibration match had the same fixed duration as the others in the same session.

The games have a fixed set of animations and sounds, which had not influenced, according to the results, the performance of the subjects. However, it is not known whether

a different set or the addition of more animations and sounds could influence this result.

The sessions were planned to occur in sequential days for each subject, but some sessions had a longer interval between each other. The effects of these intervals in the performance are unknown. To minimize this issue in this experiment, the availability to attend to all sessions of the experiment in the time span of one week was a requisite for the subjects to participate in the study.

6 The Influence of Social Interaction on Users' Performance and Game Experience

In this chapter, an experiment using a multiplayer attention-based BCI game is described. This experiment aimed to analyze both qualitative and quantitative aspects of the subjects' interaction with the BCI platform, the game itself, and with the other player, focusing on the influence of the social interaction and the multiplayer game mode (i.e. competitive or collaborative) on the player's performance and game experience. Based on these objectives, the experiment is guided by the following Research Questions (**RQs**):

- **RQ1:** Is there a difference in performance between the collaborative and the competitive groups?
- **RQ2:** Is there a difference in the game experience between the collaborative and the competitive groups?

The investigation of such factors may help designing future multiplayer neurofeedback-based games focused on either of both modes of social interaction, and may help to comprehend the influence of actively interacting with other people in the subject's level of attention.

6.1 Methodology

This experiment was designed to evaluate the social aspects of a multiplayer neurofeedback game, especially regarding the interaction between players and how this interaction could have affected the performance and game experience of the subjects. This section describes the experiment's methodology.

6.1.1 Multiplayer attention-based BCI game

The multiplayer version of the Mental War game is slightly different from the single player version. In this version, the player can choose to play both competitively or collaboratively, or together or against other players or the computer. Competitively, the player can use his attention to compete against other player, against a group of players, or against both players and the computer at the same time. Collaboratively, the player can join efforts with other players against the computer, against a group of players, or both.

The game match is composed of two teams, each on one side of the arena. The rules are the same for the single player mode: the first team to successfully push the other team to the middle of the arena wins the match. Each team can be composed of one to three members, and each member can be a human or a machine player (i.e., a real person or the computer – which can be set at any of the three available difficulties of the single player mode). Additionally, it is not necessary that the teams have the same number of players, as the average attention of each member is averaged with the ones of the other members. The only requisite is that there is at least one human player in one team. Figure 28 shows a multiplayer game match with both human and machine players, with different team sizes and different difficulties for the machine players.



Figure 28: Mental War multiplayer match.

The averaged values of each team allows for a more collaborative gameplay, as both members should maintain their average attention high enough so the mean attention is higher than the other team. Also, it allows for one single player to be able to compete

with two or three other players without penalties, and to create "custom" difficulties by combining two or more machine players of different difficulty levels.

Some key features are also different from the single player mode. In the single player mode, the player force is calculated by averaging all attention values during the match. In the multiplayer mode, in order to avoid long match durations due to stagnation of the averaged value, only the last 20 attention values are considered in the average calculation. This creates a more variable force values during the match, allowing for the player to recover from a period of low attention, and forcing him/her to maintain the attention high during all match. The game scenario is also different: in contrast to harsher scenarios related to increased difficulties, the multiplayer scenario is a neutral snowy mountain, as there is no intrinsic difficulty associated with the match.

6.1.2 Research Questions

The first research question, RQ1, involves the investigation of a possible difference in performance due to the social interaction during the BCI game, i.e., whether playing competitively or collaboratively significantly impacts the average attention of the players in a neurofeedback-based game. The main hypothesis is that the social presence of other players and the pressure to keep a better performance in comparison to them may disrupt or increase the focused attention of the subject.

The second research question, RQ2, is aimed at investigating whether there is a difference in the overall game experience while comparing both modes of social interaction. In this case, the main hypothesis is that the player may perceive a better or worse game experience depending on the mode they are playing, especially in relation to the social presence of the other player and how they are interacting, competitively or collaboratively.

6.1.3 Participants

The experiment was conducted with sixteen volunteer subjects (S1-S16), being twelve male and four female. Participants ranged from 20 to 32 years ($M = 24.81$, $SD = 2.66$). The only adopted selection criteria was that the participants had no metal plate implants in the region of the forehead.

6.1.4 Ambient and Materials

The same two computers were used by all subjects for all sessions of the experiment. The experiment was conducted in a closed and climatized room. The computers are equipped with an Intel Core 2 Duo processor, 4 GB RAM, Windows 7 64-bits operational system and a 15" monitor, adjusted to the subjects' height. All sessions were recorded with the participants' consent, using four Microsoft LifeCam Cinema cameras connected to two other computers in order to avoid any possible performance loss in the game. The headsets employed to acquire the subjects' brain signals were two NeuroSky MindWave, both model MW001.

The Game Experience Questionnaire (GEQ) (POELS; KORT; IJSELSTEIJN, 2007; NORMAN, 2013) was employed in this experiment for help answering the research questions and to gather more information about the subjects' interaction with the game. The GEQ is divided into three modules, each assessing different components of game experience: the core module, the social presence, and the post-game module. The core module assesses game experience based on immersion, flow, competence, positive affect, negative affect, tension and challenge. The social presence module assesses psychological and behavioral involvement of the player with other entities or players. The post-game module assesses how players felt after they had stopped playing. Each module is composed of several items, which should be answered using a 5-point unipolar intensity-based scale, with points ranging from "not at all" (0) to "extremely" (4). The intensity of the component is calculated as the average of the value of its items. Examples of items are "I was deeply concentrated in the game", from the core module, and "My actions depended on the other(s) actions", from the social presence module.

6.1.5 Procedure

Each subject had to participate in only one session of the experiment, which has one pair of subjects and was recorded with the four digital cameras. In the beginning of the session, the two subjects filled out a demographic form and the researcher explained the experiment. The subjects were free to ask any question at any time, and both watched one video that shows how the game works and how it is played with the BCI device. The eight pairs of subjects were divided into two groups of equal size: the collaborative group, in which each pair played the game collaboratively to try to defeat the machine; and the competitive group, in which each pair of subjects played against each other. To assure internal validity, the pairs of subjects were randomly assigned to each group.

Before playing in groups, each subject played an individual, single player match for 30 seconds to assure that there was a stable connection with the BCI device. Then, five multiplayer matches were played in the session. At the end of the session, each player was asked to answer a GEQ form in order to gather more information on the subjects' experience from the five matches.

After each match, a short semi-structured interview was conducted with the participant to acquire relevant information about the match, such as what strategy he used to play, if he felt tired or fatigued, whether he found the match to be difficult, and general observations that emerged during the match. These interviews were used to assure that the subject would give more precise answers, as he had played the match just moments before.

6.1.6 Design

The experiment has a between-subject design, as each user is assigned to a group and each group tested for only one task. The independent variable is the interaction mode with the game, with two levels (collaborative and competitive). The dependent variables were the average attention of the participant and his/her scores for the three GEQ forms, all acquired at the end of the session.

6.2 Results

The results were divided and presented according to each research question separately. The analysis of the experiment data includes both quantitative and qualitative aspects of the interaction of the users in the five matches that each one played. The quantitative results were obtained by applying a number of statistical analyses on the dependent variables, i.e., the output of the matches: the subject's average level of attention and the scores for the GEQ form. A D'Agostino & Pearson normality test was applied to guarantee the normal distribution of the values in all statistical analyses.

6.2.1 RQ1: Is there a difference in performance between the collaborative and the competitive groups?

To address this research question, an independent samples t-test was applied to compare the average score of the five matches that each of the eight subjects of each group played.

The test revealed that there is no significant statistical difference between the average performance of both groups, $t(14) = 0.239$, $p = .814$. Table 14 presents the average attention scores of all matches from both groups.

Table 14: Statistics of average attention for all matches from both groups

Statistic	Competitive matches					Collaborative matches				
	M1	M2	M3	M4	M5	M1	M2	M3	M4	M5
Minimum	50.2	42.3	42.8	37.7	38.6	35.6	27.2	30.2	36.4	27.6
25% Percentile	50.4	47.3	50.6	47.0	45.6	48.3	42.7	46.2	43.0	35.1
Median	56.1	52.9	57.7	51.4	50.9	61.5	61.7	58.3	50.2	45.2
75% Percentile	58.5	57.9	61.0	68.2	56.3	71.8	63.7	64.2	60.6	56.6
Maximum	74.3	68.4	70.8	84.7	67.3	88.3	72.3	71.9	74.0	67.5
Mean	56.8	53.4	56.5	56.8	51.6	61.0	54.1	54.7	52.6	46.7
Std. Deviation	7.94	8.90	9.02	15.6	9.45	18.5	16.6	14.0	13.0	14.8

In order to further investigate the differences between the two groups, the data were also analyzed in terms of the individual matches, i.e., if there are any differences in the performance based on the number of matches played by each subject from both groups. As each match was played consecutively, a repeated-measures two-way ANOVA was applied by considering the matches as a within-subject time factor and the groups as the between-subject treatment factor. This allowed analyzing not only the differences between the groups, but the influence of the number of matches that each subject played on his average attention (e.g. fatigue effects) and whether this effect is the same for both groups. Therefore, the IVs are the group condition, with two levels (competitive and collaborative), and the time, with five levels (i.e. the matches, from the first to the fifth). The DV is the average attention score.

Mauchly's sphericity test for the repeated measures is shown in Table 15. The main effect of time (matches) significantly violated the sphericity assumption, as the significance value is lower than 0.05 for the average attention, $W = 0.248$, $X^2(9) = 17.289$, $p = .046$. Therefore, the degrees of freedom for the main effect of time and its interaction with the between-group variable were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.656$). Levene's test for equality of variances was non-significant for matches M3, M4 and M5, but significant for matches M1 ($p = .034$) and M2 ($p = .042$). The choice of using the RM two-way ANOVA was kept nevertheless, as it is fairly robust when considering equal samples sizes and a relatively high significance value.

For the within-subjects effects, the test revealed that there is no significant main effect of time, $F(2.62, 36.7) = 2.17$, $p = .116$. This result suggest that, when considering only

Table 15: Mauchly's test for sphericity.

Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon		
					Greenhouse- Geisser	Huynh- Feldt	Lower- Bound
Time (Matches)	0.248	17.289	9	.046	0.656	0.878	0.250

the time and ignoring the group factor, the number of matches that the subjects played does not have a significant effect on their average attention score. However, post hoc pairwise tests using Bonferroni adjustments showed a significant difference on the means of the first and fifth match ($p = .024$). Table 16 shows the statistics for all matches of both groups.

Table 16: Statistics of average attention from all matches.

Statistic	Match				
	M1	M2	M3	M4	M5
Minimum	35.6	27.2	30.2	36.4	27.6
25% Percentile	50.4	45.3	47.7	43.9	41.9
Median	57.8	55.6	57.7	51.4	48.4
75% Percentile	65.7	62.0	63.7	66.2	56.3
Maximum	88.3	72.3	71.9	84.7	67.5
Mean	58.9	53.8	55.6	54.7	49.2
Std. Deviation	13.9	12.9	11.4	14.1	12.2

Based on this result and the data from the Table X, the mean attention of the first match is significantly greater than the mean of the fifth match, indicating that the subjects indeed may suffer from possible fatigue effects and loses performance with consecutive matches. All other pairwise comparisons were non-significant. Figure 29 presents the average attention per match, scaled in the vertical axis.

For the between-subjects effect, the test presented the same result as the independent samples t-test, as expected, $F(1, 14) = 0.06$, $p = .814$. This suggests that there is no difference in performance for both groups, i.e., subjects playing competitively had the same performance of subjects playing collaboratively. Finally, the mixed within-between subjects relation of time vs. condition also shows no statistical significant difference, $F(2.62, 36.7) = 0.611$, $p = .591$. This means that, considering both factors simultaneously, there is no difference between the average attention of both groups in relation to time, i.e., the effects of time are the same for both groups. Figure 30 presents the average meditation per match of all subjects, scaled in the vertical axis. The figure shows corroborates with the results, as the average attention indeed decreases over time, but this

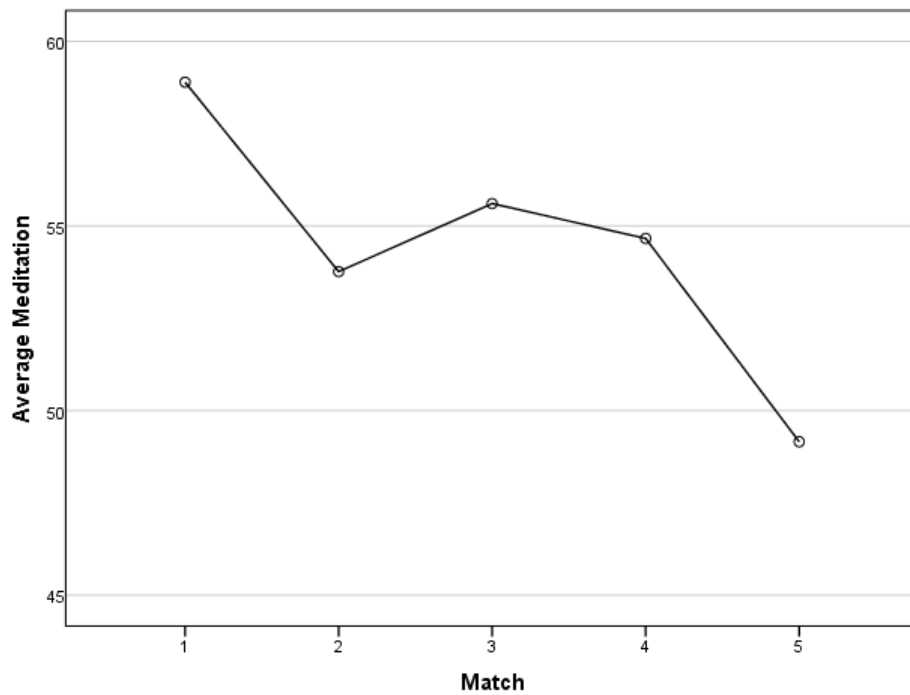


Figure 29: Average attention per match from all subjects.

decrease is virtually the same for both groups.

6.2.2 RQ2: Is there a difference in the game experience between the collaborative and the competitive groups?

As stated in the procedures section, at the end of the session each subject had to fill out a GEQ form, which measures various aspects of the game experience and will help to answer this research question. The GEQ was chosen for this analysis as it not only provides insights regarding the overall game experience during and after the game, but it also has a specific module designed to analyze the social presence of the game, i.e., how do players perceive and feel about the social interaction while playing the game. The results will be presented by comparing the scores, which ranges from zero to four, for each component of the core, social presence, and post-game modules of the GEQ.

The core module measures seven components: Competence, Sensory and Imaginative Immersion, Flow, Tension/Annoyance, Challenge, Negative Affect, and Positive Affect. In general, the competitive group had higher scores for all components, except for challenge and negative affect. Table 17 gives the average points in each component for both groups.

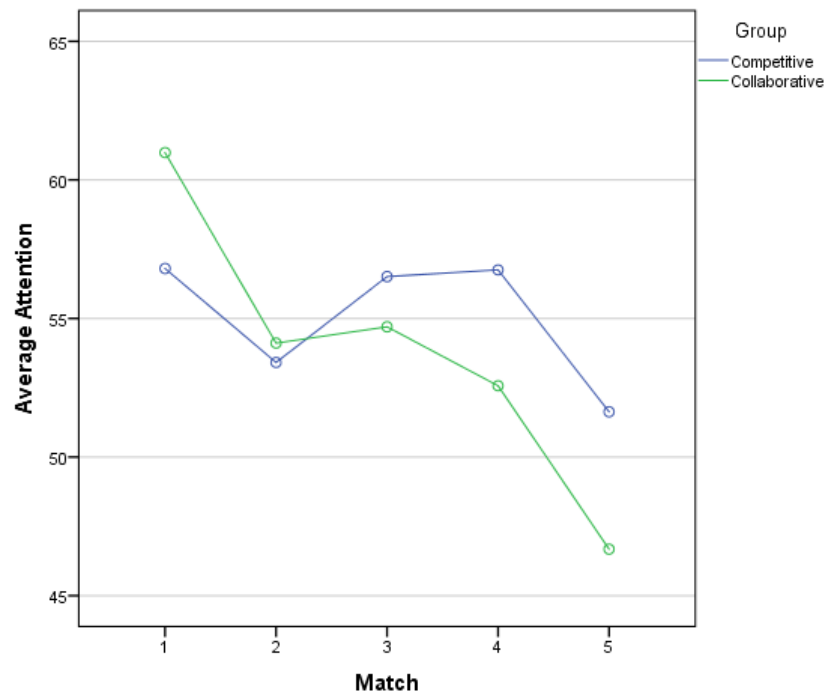


Figure 30: Average attention per match for both groups.

Table 17: Average scores of the core module components for both groups.

Component	Competitive	Collaborative	Difference
Competence	2.13	1.37	0.76
Sensory and Imaginative Immersion	2.25	1.69	0.56
Flow	2.08	1.90	0.18
Tension/Annoyance	0.71	0.67	0.04
Challenge	1.75	1.83	0.08
Negative affect	0.88	1.17	0.29
Positive affect	2.68	1.87	0.81

The social presence module measures three components: Empathy, Negative Feelings, and Behavioral Involvement. All scores were higher for the competitive group. However, the behavioral involvement component had almost no difference between the groups. The negative feelings components had the highest difference, with 0.73 points. Table 18 gives the average points in each component for this module.

Table 18: Average scores of the social presence module components for both groups.

Component	Competitive	Collaborative	Difference
Empathy	2.19	1.60	0.58
Negative Feelings	1.68	0.95	0.73
Behavioral Involvement	1.48	1.46	0.02

Finally, the post-game module has four components: Positive Experience, Negative Experience, Tiredness, and Returning to Reality. All components were higher for the competitive groups, with exception of the Negative Experience component. Table 19 shows the average points of this module.

Table 19: Average scores of the core module components for both groups.

Component	Competitive	Collaborative	Difference
Positive Experience	1.83	1.23	0.60
Negative experience	0.33	0.50	0.17
Tiredness	0.81	0.56	0.25
Returning to Reality	0.67	0.33	0.33

Based on the values of each module, it appears that the subjects of the competitive group had an overall better experience playing the game. The differences in some key components were much higher, with over half-point of difference in the Competence, Positive Affect, Sensory and Imaginative Immersion, Empathy, and Positive Experience. Also, the value for the Negative Affect and Negative Experience are lower than the collaborative group. However, the Negative Feelings component has a 0.73 points higher value in the competitive group in comparison to the collaborative group.

6.3 Limitations

As the algorithm used by the BCI EEG equipment is unknown, a calibration match occurred at the beginning of the session to avoid any accuracy issue related to a possible learning feature of the headset. However, even if the result of this match is excluded from the evaluation of the experiments, its occurrence may have influenced the results of the following matches, as the subject gathers more experience and it may increase

his/her fatigue. To minimize this issue this experiment, this calibration match had a fixed duration of 30 seconds.

As with the other two experiments, there had been cases of subjects reporting to be feeling tired, hungry, stressed, or having had a poor night of sleep. Any possible influence of lack of sleep, tiredness, and cerebral hematic changes due to food or hormonal factors are beyond the control of the researchers. Also, the sample size (sixteen subjects, eight pairs) may be considered small for a comparative study. In future studies, it would be interesting to have a bigger sample size.

To minimize the effects of subject fatigue during the experiment, it would be prudent to conduct shorter sessions (e.g. three matches instead of five per session). In this particular experiment, the number of matches was kept at five nevertheless as the fatigue effect was also investigated.

7 Final Remarks

This research presented the reporting of a systematic literature review of consumer-grade BCI-based games following the PRISMA guidelines. Based on the results of the systematic review, three experiments were elaborated in order to investigate key aspects of the user interaction of these games. The experiments were performed with a total of 40 subjects, who played a total of 424 matches of the two developed BCI-based games. The quantitative and qualitative results of these three experiments were presented and discussed. This research involved the application and evaluation of tools from various fields, such as computer science, neuroscience, medicine and psychology, and its results may benefit programmers, developers, designers and researchers, especially those from the areas of human-computer interaction and brain-computer interfaces.

The review was conducted in three search engines for papers from 2007 to April 2016 and, from the initial 2,261 initial articles found and after several phases of refinement, 50 final articles were analyzed, from which data of 46 games were gathered. The collected data allowed drawing reflections based on the reviewed games' characteristics, as well as open topics and challenges that need to be overcome in order to advance in the field of BCI-based games, especially those using consumer-grade EEG devices.

The main findings of this review are related to the nature of the reviewed games. The majority of those games were created with simplified controls to be applied as training tools and to test the performance of BCI techniques. Most games that were not adapted from existing ones also have limited visual design and sounds. In general, comparing to the results of past reviews, it is certain that there was an increased effort in making the games more attractive and user-friendly in the last years, both in visual aspects and gameplay mechanics. However, there are still many open issues that are yet to be addressed in order to make such games appealing to the general public, and popular not only as a research tool. Furthermore, BCI control was employed in a vast diversity of games of different genres and, despite the limitations of the technology, it is clear that BCI can be used to increase immersion and create new interactions as both an active or passive controller.

The first experiment, aiming at investigating the influence of graphical elements on such games, was conducted with eight subjects, who played a total of 240 matches. The experiment shows that the game may help to improve one's attention over time, as the average values of the last half of the matches were higher than the first. However, the participants did not feel any improvement on their control over the game, even with increased performance, as indicated by the qualitative results. The experiment's results also show that there is no significant difference in the subjects' average attention in the matches with and without the game's graphical user interface, indicating that the visual elements of the game had no positive or negative influence on the performance of the players. Also, there was also no difference in the subjects' performance based on the game difficulties, and no difference in the duration of the matches with or without the graphical elements. These results may help game designers, developers and researchers on the design and implementation of BCI-based attention games.

The second experiment was conducted with 16 subjects divided into two groups, each playing a different game condition over three sessions, with a total of 144 game matches. The experiment aimed to investigate the influence of the auditory stimuli, e.g. sound effects, in the subjects' average meditation and self-assessed workload in both groups, and how both variables change over time. The experiment's results suggest that the performance of the subjects may increase over time, as the subjects performed better in each consecutive session, regardless of the condition. Although the difference is not statistically significant, there is a linear trend to an increased average meditation in relation to time. Also, there is no significant statistical difference in performance from the subjects playing with or without the auditory stimuli, suggesting that the sound effects in the game had no impact in the average meditation. Finally, there is no difference in the workload in relation to both groups. Although the group playing without the auditory stimuli presented lower average workload across the sessions, the difference is not statistically significant, nor is the main effect of time. However, like the average meditation, there is a negative linear trend of workload in relation to time, i.e. the self-assessed, perceived workload may decrease the more the subjects play.

Finally, the third experiment was also conducted with 16 subjects divided into two groups of eight pairs, each playing five matches of the game in a different condition, with a total of 40 matches. This experiment aimed to investigate the influence of social interaction on both conditions, i.e. competitively and collaboratively, in the subjects' performance and game experience. The experiment's results showed that, although there is no statistically significant difference in performance between the competitive and the

collaborative groups, there are specific differences in the game experience from playing the competitively and playing collaboratively. The game experience questionnaire showed that the players in the competitive groups had an overall better experience, as various metrics had a higher value in comparison to the collaborative group. Also, there is a statistically significant difference in the players performance from the first to the last matches of the sessions, indicating that playing many consecutive matches of attention-based games may cause fatigue effects and lower the average attention of the subject over time.

7.1 Main Contributions

The main contributions of this work are related to the results of the systematic review and the controlled experiments. For the systematic review, the main contributions are a critical, comprehensive and systematic literature review of the field of BCI games using consumer-grade EEG devices; a detailed and extensive description of researches from the past ten years on the field, as well as an analysis on the evolution of these works over the years; and a highlight on the challenges, gaps, trends, and open problems of the field, as well as guidance for future researches based on its results.

For the experiments, the main contributions are their statistical results and the in-depth discussion of its implications to the field; a detailed analysis on the qualitative aspects of the subjects' interaction with the BCI games, and which consequences did the games design had in the subjects' performance; a better comprehension on the role of graphical elements in BCI attention-based games, both in relation to the performance of the players and their perceived control over the game; a better comprehension on the role of auditory stimuli in BCI meditation-based games, both in relation to the performance of the players and their self-assessed workload over the game; and a better comprehension on the effects of different kinds of social interaction on the performance and game experience in multiplayer BCI games.

7.2 Future Works

As future works, it would be interesting to conduct the studies with a larger number of subjects and a larger number of sessions. Also, conducting the experiments with groups of people with specific ranges of age (e.g. children or elders) may lead to interesting results.

Some of the design choices for the experiments were made taking into consideration

that focused visual contact generally increases the average attention of the subject, and that closing the eyes usually leads to a higher average meditation. It would be interesting to assess how the average attention and meditation of blind subjects would behave in such games, as there is no possible visual contact. On the other hand, a possible study would be to investigate how the performance of players are affected while playing a virtual reality game, as there is a full visual immersion with the scenario.

Finally, it would also be interesting to investigate the influence of visual and auditory stimuli on games using other control signals, such as SSVEP (which is highly dependent on stable stimuli to work properly), P300 and motor imagery.

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APPENDIX A – Additional Data from the Games

This supplementary material presents basic and additional data retrieved from the games, such as information regarding its development and evaluation. Table A.1 shows the primary data collected from the games, such as which consumer-grade EEG device was used; which BCI control signal it employed; the genre of the game; its primary development purpose; in which platform it is intended to be played; and whether it uses its BCI control in an active or passive manner, or if it can be used in both ways.

Table 20: Basic data of the reviewed games.

Game	Reference	BCI Device	BCI Control Signal	BCI Paradigm	Game Genre	Game Purpose	Game Platform
G1	(QIANG; SOURINA; KHOA, 2010) (SOURINA et al., 2011)	Epoc	Attention	Active	Action	Health care	PC
G2	(HOU; SOURINA, 2013)	Epoc	Emotion	Passive	Simulation	Health care	PC
G3	(MUNOZ et al., 2015)	MindWave	Attention	Active	Adventure	Health care	PC
G4	(POULIOS; ELIENS, 2013)	MindWave	Attention, Meditation	Active	Puzzle	Education	PC
G5	(AL-RUBAIAN et al., 2014)	Epoc	Motor Imagery, Emotion	Active, Passive	Puzzle	Health care	PC
G6	(HJORUNGDAL et al., 2016)	Epoc	Motor Imagery	Active	Simulation	Training	PC
G7	(CHARISIS et al., 2015)	Epoc	Emotion	Active	Action	Training	PC
G8	(MUNOZ et al., 2013)	Epoc	SSVEP	Active	Action	Health care	PC
G9	(SOURINA; LIU, 2014)	Epoc	Emotion	Passive	Puzzle	Education	PC
G10	(HENRIK et al., 2011)	Epoc	Emotion	Active, Passive	Action	Training	PC
G11	(SCHWARZ et al., 2014)	Epoc	Motor Imagery	Active	Sport	Education	PC
G12	(SCHWARZ et al., 2014)	Epoc	Motor Imagery, Attention	Active	Action	Education	PC
G13	(CHO; LEE, 2014)	MindSet	Attention, Meditation	Passive	Action	Entertainment	PC
G14	(LIU; SOURINA; HOU, 2014) (LIU; HOU; SOURINA, 2015)	Epoc	Attention	Active	Action	Training	PC
G15	(WANG; LARSEN, 2012)	MindSet	Attention, Blink	Active	Action	Research	PC
G16	(VOURVOPOULOS; LIAROKAPIS; PETRIDIS, 2012) (LIAROKAPIS et al., 2013) (LIAROKAPIS et al., 2014)	Epoc, MindSet	Motor Imagery, Attention, Meditation, Blink	Active	Simulation	Education	PC
G17	(CRAWFORD et al., 2015)	Epoc	Motor Imagery	Active	Simulation	Research	PC
G18	(FERNANDEZ et al., 2016)	MindWave	Attention	Passive	Action	Research	PC
G19	(HSIEH; CHU; HUANG, 2014)	Epoc	Eye Tracking	Active	Puzzle	Research	Web
G20	(WU; XIE; WANG, 2014)	MindSet	Attention, Meditation	Active	Sport	Entertainment	Mobile
G21	(THOMAS; VINOD; GUAN, 2014) (THOMAS; VINOD; GUAN, 2013a) (THOMAS; VINOD; GUAN, 2013b)	Epoc	Attention	Active	Puzzle	Training	PC
G22	(WEINEL et al., 2015)	MindWave	Attention, Meditation	Passive	Action	Research	PC
G23	(KOS'MYNA; TARPIN-BERNARD, 2013)	Epoc	SSVEP, Motor Imagery	Active	Puzzle	Research	PC
G24	(VLIET et al., 2012)	Epoc	SSVEP	Active	Strategy	Entertainment	PC
G25	(LIM et al., 2012)	Other device	Attention	Active	Action	Health care	PC
G26	(COULTON; WYLIE; BAMFORD, 2011)	MindSet	Attention, Meditation	Active, Passive	Action	Research	Mobile
G27	(VERPLAETSE et al., 2016)	Epoc	SSVEP, Motor Imagery	Active	Simulation	Health care	PC
G28	(LAAR et al., 2013) (GÜRKÖK et al., 2014)	Epoc	Meditation	Active, Passive	RPG	Entertainment	PC
G29	(MARTISIUS; DAMASEVICIUS, 2016)	Epoc	SSVEP	Active	Action	Research	PC
G30	(YANG; LEUNG, 2013)	Epoc	VEP	Active	Puzzle	Research	PC
G31	(YOON et al., 2013)	MindWave	Attention	Active	Action	Research	PC
G32	(KIM; CHO, 2014)	Epoc	Motor Imagery	Active	Sport	Research	PC
G33	(WONG et al., 2015)	Epoc	SSVEP	Active	Action	Research	PC
G34	(JOSELLI et al., 2014)	MindWave	Attention	Passive	Action	Entertainment	Mobile
G35	(ANTLE et al., 2015)	MindWave	Meditation	Active	Action	Training	Mobile
G36	(ANTLE et al., 2015)	MindWave	Meditation	Active	Action	Training	Mobile
G37	(ANTLE et al., 2015)	MindWave	Attention	Active	Action	Training	Mobile
G38	(JIANG; JOHNSTONE, 2015)	MindWave	Meditation	Active	Sport	Health care	PC
G39	(KHONG et al., 2014)	Epoc	Attention	Active	Action	Training	PC
G40	(LIAROKAPIS; VOORVOPOULOS; ENE, 2014)	MindSet	Meditation	Passive	Puzzle	Entertainment	PC
G41	(SHENJIE et al., 2014)	Epoc	Attention	Active	Sport	Training	PC
G42	(HAZRATI; HOFMANN, 2013)	Epoc	Motor Imagery	Active	Simulation	Entertainment	PC
G43	(PODOPRIKHIN, 2015)	Epoc	Blink	Active	Action	Research	PC
G44	(CHUMERIN et al., 2013)	Epoc	SSVEP	Active	Action	Entertainment	PC
G45	(LEE et al., 2013)	Other device	Attention	Active	Puzzle	Training	PC
G46	(KO et al., 2009)	MindSet	Attention, Meditation	Active	Adventure	Entertainment	PC

Table A.2 presents information regarding the development of the games, such as whether the game is single or multiplayer, whether it can be played over a network, whether it is an adaptation of an already existing game, its programming language, which frameworks were employed and which complementary tools were used to help to create the game.

Table 21: Development data from the games.

Game	Single/multi player	Network	Adapted	Language	Framework	Engine	Tools
G1	Single	No	No	C++	SDL	n/a	n/a
G2	Single	No	No	n/a	CHAI 3D	ODE	NOVINT Falcon
G3	Single	No	No	n/a	n/a	Unity	n/a
G4	Single	No	No	C#	OpenNI SDK	Unity	Kinect, Zephyr HxM
G5	Single	No	No	C#	n/a	n/a	EmoEngine
G6	Single	No	No	n/a	n/a	Unity	MatLab
G7	Single	No	No	C#	.Net	Unity	Matlab
G8	Single	No	No	n/a	OpenVIBE	n/a	Kinect
G9	Single	No	No	n/a	n/a	n/a	n/a
G10	Single	No	No	n/a	n/a	Unity	n/a
G11	Multi	No	Yes	C++	Cocos2s	n/a	n/a
G12	Single	No	Yes	C++	Cocos2s	n/a	n/a
G13	Single	No	Yes	n/a	n/a	Unity	n/a
G14	Single	No	No	n/a	n/a	n/a	n/a
G15	Single	No	Yes	C#	.Net	n/a	n/a
G16	Single	No	Yes	C#, JavaScript	LoI	Unity	n/a
G17	Multi	No	No	JavaScript	n/a	n/a	n/a
G18	Single	No	No	n/a	n/a	n/a	n/a
G19	Single	No	Yes	n/a	n/a	n/a	n/a
G20	Single	No	No	n/a	n/a	n/a	OpenGL
G21	Single	No	No	n/a	n/a	n/a	n/a
G22	Single	No	Yes	n/a	n/a	n/a	n/a
G23	Single	No	No	n/a	OpenVIBE	n/a	Tobii T60 eye tracker
G24	Single	No	No	n/a	n/a	Unity	NumPy, SciPy, GolemML/PsychicML
G25	Single	No	No	n/a	n/a	n/a	n/a
G26	Single	No	No	n/a	n/a	n/a	n/a
G27	Single	No	No	n/a	n/a	Unity	Blender
G28	Multi	Yes	Yes	n/a	n/a	n/a	n/a
G29	Single	No	No	n/a	OpenVIBE	n/a	n/a
G30	Single	No	No	n/a	n/a	n/a	n/a
G31	Single	No	No	C++	n/a	n/a	n/a
G32	Single	No	Yes	n/a	n/a	n/a	n/a
G33	Single	No	No	C++	DirectX SDK	n/a	MatLab, Simulink
G34	Single	No	Yes	Objective-C	Cocos2d, iPhone SDK	n/a	n/a
G35	Single	No	No	n/a	n/a	Unity	n/a
G36	Single	No	No	n/a	n/a	Unity	n/a
G37	Single	No	No	n/a	n/a	Unity	n/a
G38	Single	No	No	n/a	n/a	n/a	n/a
G39	Multi	Yes	No	n/a	Photon Network	Unity	MatLab
G40	Single	No	Yes	Java	n/a	n/a	n/a
G41	Single	No	No	C#	n/a	n/a	n/a
G42	Multi	Yes	Yes	C++	Emotiv SDK	n/a	n/a
G43	Single	No	No	n/a	n/a	MatLab	n/a
G44	Single	No	No	n/a	n/a	MatLab	n/a
G45	Single	No	No	n/a	n/a	n/a	n/a
G46	Single	No	No	n/a	.Net	XNA	n/a

Table A.3 presents information regarding experiments and/or the evaluation of the game itself, such as which quantitative and qualitative methods were employed, how many subjects participated in the evaluation/experiment and how many sessions it had. For games with more than one reference, the data from each reference is presented separately. Only experiments and evaluations which directly employed and evaluated the games were considered.

The empirical strategy classification is based on the definitions of Wohlin et al. (2012), who divides the empirical strategies into surveys, case studies and (controlled) experiments. It is worth noticing that, although some works performed an evaluation, the empirical strategy may still be listed as "n/a" if there are not enough details regarding the employed methodologies in the paper. For the quantitative methods, any statistical and numerical analyses were considered, given that it was measured while interacting with the game itself. Performance measures, such as accuracy, precision, time to complete a task and average attention and meditation values were also considered.

Table 22: Evaluation and experimentation data from the games.

Game	Reference	Empirical Strategy	Qualitative Methods	Quantitative Methods	Subjects	Sessions
G1	(QIANG; SOURINA; KHOA, 2010)	n/a	n/a	n/a	n/a	n/a
	(SOURINA et al., 2011)	n/a	n/a	n/a	n/a	n/a
G2	(HOU; SOURINA, 2013)	Case study	Interview	n/a	4	1
G3	(MUNOZ et al., 2015)	n/a	n/a	n/a	n/a	n/a
G4	(POULIOS; ELIENS, 2013)	n/a	n/a	n/a	n/a	n/a
G5	(AL-RUBAIAN et al., 2014)	n/a	n/a	n/a	n/a	n/a
G6	(HJORUNGDAL et al., 2016)	n/a	n/a	n/a	3	n/a
G7	(CHARISIS et al., 2015)	n/a	n/a	n/a	n/a	n/a
G8	(MUNOZ et al., 2013)	n/a	n/a	n/a	n/a	n/a
G9	(SOURINA; LIU, 2014)	n/a	n/a	n/a	n/a	n/a
G10	(HENRIK et al., 2011)	Case study	Interview, questionnaires	Performance	6	1
G11	(SCHWARZ et al., 2014)	Survey	n/a	n/a	60	1
G12	(SCHWARZ et al., 2014)	Survey	n/a	n/a	60	1
G13	(CHO; LEE, 2014)	Case study	n/a	n/a	6	1
G14	(LIU; SOURINA; HOU, 2014)	Case study	n/a	Performance	3	6
	(LIU; HOU; SOURINA, 2015)	Experiment	n/a	Kruskal-Wallis, t-test	40	6
G15	(WANG; LARSEN, 2012)	Case study	n/a	Performance	n/a	1
G16	(VOURVOPOULOS; LIAROKAPIS; PETRIDIS, 2012)	Case study	Interview	n/a	5	1
	(LIAROKAPIS et al., 2013)	Case study	Questionnaire	n/a	61	1
	(LIAROKAPIS et al., 2014)	Experiment	Questionnaire	Kolmogorov-Smirnov, Whitney-Mann	61	1
G17	(CRAWFORD et al., 2015)	Case study	n/a	Performance	3	1
G18	(FERNANDEZ et al., 2016)	Case study	n/a	Performance	25	1
G19	(HSIEH; CHU; HUANG, 2014)	Case study	n/a	Performance	11	1
G20	(WU; XIE; WANG, 2014)	Case study	n/a	Performance	5	1
G21	(THOMAS; VINOD; GUAN, 2014)	Experiment	n/a	Performance, t-test	5	1
	(THOMAS; VINOD; GUAN, 2013a)	Experiment	n/a	Performance	8	5
	(THOMAS; VINOD; GUAN, 2013b)	Case study	n/a	Performance	3	1
G22	(WEINEL et al., 2015)	Case study	Questionnaire	t-test	10	1
G23	(KOS'MYNA; TARPIN-BERNARD, 2013)	Experiment	Interview	Performance, ANOVA	30	1
G24	(VLIET et al., 2012)	Case study	Questionnaire	Performance	25	1
G25	(LIM et al., 2012)	Experiment	n/a	t-test	17	27
G26	(COULTON; WYLIE; BAMFORD, 2011)	Case study	Questionnaire	Performance	40	1
G27	(VERPLAETSE et al., 2016)	Case study	n/a	Performance	1	n/a
G28	(LAAR et al., 2013)	Experiment	Questionnaire	Performance, MANOVA	42	1
	(GÜRKÖK et al., 2014)	Case study	Interview	n/a	42	1
G29	(MARTISIUS; DAMASEVICIUS, 2016)	Case study	n/a	Performance	2	1
G30	(YANG; LEUNG, 2013)	Case study	n/a	Performance	5	1
G31	(YOON et al., 2013)	Case study	SAM	Performance	42	1
G32	(KIM; CHO, 2014)	Experiment	n/a	Performance, t-test	10	n/a
G33	(WONG et al., 2015)	Case study	n/a	Performance	20	1
G34	(JOSELLI et al., 2014)	Case study	Interview	Performance	11	n/a
G35	(ANTLE et al., 2015)	Experiment	Questionnaire	t-test, ANOVA	22	n/a
G36	(ANTLE et al., 2015)	Experiment	Questionnaire	t-test, ANOVA	22	n/a
G37	(ANTLE et al., 2015)	Experiment	Questionnaire	t-test, ANOVA	22	n/a
G38	(JIANG; JOHNSTONE, 2015)	Experiment	Interview	T-Score, Cohen's d	5	25
G39	(KHONG et al., 2014)	Case study	n/a	Performance	3	3
G40	(LIAROKAPIS; VOORVOPOULOS; ENE, 2014)	Experiment	Interview	Performance, Wilcoxon	30	1
G41	(SHENJIE et al., 2014)	Experiment	n/a	Performance	4	3
G42	(HAZRATI; HOFMANN, 2013)	Experiment	n/a	Performance	3	1
G43	(PODOPRIKHIN, 2015)	n/a	n/a	n/a	1	3
G44	(CHUMERIN et al., 2013)	Experiment	Questionnaire	Wilcoxon signed rank	73	1
G45	(LEE et al., 2013)	Experiment	Questionnaire	t-test, Mann-Whitney	31	24
G46	(KO et al., 2009)	Experiment	Questionnaire	t-test	20	1

Tables A.4 and A.5 present a summary of the games using the attention and meditation signals, along with which BCI device and technique were employed to calculate the estimated value.

Table 23: Attention estimation techniques employed by each game.

Game	BCI device	Meditation estimation
G1	Epoc	Fractal dimension
G3	MindWave	Theta/beta ratio
G4	MindWave	eSenses
G12	Epoc	Beta
G13	MindSet	eSenses
G14	Epoc	Alpha, beta/theta ratio (LIU; SOURINA; HOU, 2014), Fractal dimension, theta/beta ratio (LIU; HOU; SOURINA, 2015)
G15	MindSet	Power spectrum
G16	MindSet	eSenses
G18	MindWave	n/a
G20	MindSet	eSenses
G21	Epoc	Entropy
G22	MindWave	eSenses
G25	Other device	Power spectrum
G26	MindSet	eSenses
G31	MindWave	eSenses
G34	MindWave	eSenses
G37	MindWave	eSenses
G39	Epoc	Alpha/theta ratio, Beta/alpha ratio, Entropy
G41	Epoc	Theta/beta ratio
G45	Other device	Power spectrum
G46	MindSet	eSenses

Table 24: Meditation estimation techniques employed by each game.

Game	BCI device	Meditation estimation
G4	MindWave	eSenses
G13	MindSet	eSenses
G16	MindSet	eSenses
G20	MindSet	eSenses
G22	MindWave	eSenses
G26	MindSet	eSenses
G28	Epoc	Alpha
G35	MindWave	eSenses
G36	MindWave	eSenses
G38	MindWave	eSenses
G40	MindSet	eSenses
G46	MindSet	eSenses

APPENDIX B – List of Excluded Works

In order to promote a better transparency of the search process, the list of all excluded articles is provided. The list is in alphabetical order. The phase in which the article was excluded is presented after the semicolon at the end of each title.

'Midas touch' in human-robot interaction: Evidence from event-related potentials during the ultimatum game; EC.

"My Virtual Dream": Collective neurofeedback in an immersive art environment; EC.

"Brain Invaders": A prototype of an open-source P300-based video game working with the OpenViBE platform; EC.

"Generic Shooter 3000": A realistic first person shooter powered by biofeedback; EC.

2D vs 3D visualization and social networks entertainment games: A human factor response case study; EC.

3D fatigue from stereoscopic 3D video displays: Comparing objective and subjective tests using electroencephalography; EC.

A 3D learning playground for potential attention training in ADHD: A brain computer interface approach; EC.

A BCI contents development method based templates; EC.

A BCI-based application in music: Conscious playing of single notes by brainwaves; EC.

A binary method for simple and accurate two-dimensional cursor control from EEG with minimal subject training; EC.

A biofeedback game for training arousal regulation during a stressful task: The Space Investor; EC.

A biofeedback game with physical actions; EC.

A brain computer interface for enhancing the communication of people with severe impairment; EC.

A brain-computer interface to a plan-based narrative; EC.

A breath biofeedback computer game for children with cystic fibrosis; EC.

A co-adaptive brain-computer interface for end users with severe motor impairment; EC.

A collaborative brain-computer interface; EC.

A collaborative brain-computer interface for improving human performance; EC.

A comparative study of game mechanics and control laws for an adaptive physiological game; EC.

A comparative study on the effect of audio and visual stimuli for enhancing attention and memory in brain computer interface system; QC.

A competitive brain computer interface: Multi-person car racing system; EC.

A control-theoretic approach to adaptive physiological games; EC.

- A design of BCI based environment system for immersion of FPS game; QC.
- A design of the stress relief game based on autonomic nervous system; EC.
- A development architecture for serious games using BCI (Brain Computer Interface) sensors; IC.
- A direct brain-to-brain interface in humans; EC.
- A dynamic attention assessment and enhancement tool using computer graphics; QC.
- A framework for computer interface using EEG and EMG; EC.
- A framework for processing brain waves used in a brain-computer interface; QC.
- A game-like application for dance learning using a natural human computer interface; EC.
- A general framework for innovative mobile biofeedback based educational games; EC.
- A high performance sensorimotor beta rhythm-based brain-computer interface associated with human natural motor behavior; EC.
- A high resolution EEG study of dynamic brain activity during video game play; EC.
- A hypothesis of brain-to-brain coupling in interactive new media art and games using brain-computer interfaces; EC.
- A negative association between video game experience and proactive cognitive control; EC.
- A neurofeedback video game (MindLight) to prevent anxiety in children: A randomized controlled trial; EC.
- A novel sensor-based methodology for learner's motivation analysis in game-based learning; IC.
- A P300 BCI with stimuli presented on moving objects; EC.
- A P300-based brain-computer interface with stimuli on moving objects: Four-session single-trial and triple-trial tests with a game-like task design; EC.
- A P300-based quantitative comparison between the Emotiv Epoc headset and a medical EEG device; EC.
- A pilot study of the EEG patterns of subjects with corrected vision; EC.
- A portable auditory P300 brain-computer interface with directional cues; EC.
- A possible physiological correlate for mental flow; EC.
- A practical efficient human computer interface based on saccadic eye movements for people with disabilities; EC.
- A preliminary experiment to assess the fear value of preselected sound parameters in a survival horror game; EC.
- A preliminary study on neural basis of strategic reasoning to social decision making; EC.
- A prospective study of loss of consciousness in epilepsy using virtual reality driving simulation and other video games; EC.
- A randomized controlled trial to test the effectiveness of an immersive 3D video game for anxiety prevention among adolescents; EC.
- A real-time fractal-based brain state recognition from EEG and its applications; QC.
- A real-time SSVEP-based brain-computer interface music player application; EC.
- A serious game application using EEG-based brain computer interface; EC.
- A serious game for upper limb stroke rehabilitation using biofeedback and mirror-neurons based training; EC.
- A simple communication system based on brain computer interface; EC.
- A smart way to play using brain machine interface (BMI); EC.
- A spacecraft game controlled with a brain-computer interface using SSVEP with phase tagging; EC.

- A study in user-centered design and evaluation of mental tasks for BCI; EC.
- A study of biofeedback in a gaming environment; NA.
- A theoretical and empirical approach in assessing motivational factors: From serious games to an ITS; EC.
- Accessing tele-services using a hybrid BCI approach; EC.
- Actual and imagined movement in BCI gaming; EC.
- Adaptation of hybrid human-computer interaction systems using EEG error-related potentials; EC.
- Adaptive assistance for brain-computer interfaces by online prediction of command reliability; EC.
- Adaptive brain-computer interface; EC.
- Adaptive EEG artifact rejection for cognitive games; EC.
- Adaptive rehabilitation games; EC.
- Adaptive virtual environments: A physiological feedback HCI system concept; IC.
- Adding human learning in brain-computer interfaces (BCIs): Towards a practical control modality; EC.
- Adult-like neuroelectrical response to inequity in children: Evidence from the ultimatum game; EC.
- Affective brain-computer music interfacing; EC.
- Affective computing vs. affective placebo: Study of a biofeedback-controlled game for relaxation training; EC.
- Affective computing: Measuring the player emotions in virtual reality environments; NA.
- Affective evaluation of multimodal dialogue games for preschoolers using physiological signals; IC.
- Affective gaming: A GSR based approach; EC.
- Affective interaction: Challenges at the ubiquitous computing times; EC.
- Affective learning analysis of children in a card sorting game; EC.
- Affective level design for a role-playing videogame evaluated by a brain-computer interface and machine learning methods; IC.
- Affective Pacman: A frustrating game for brain-computer interface experiments; EC.
- Agency matters! Social preferences in the three-person ultimatum game; EC.
- ALFRED Back Trainer: Conceptualization of a serious game-based training system for low back pain rehabilitation exercises; EC.
- Altered reward processing in pathological computer gamers - ERP-results from a semi-natural gaming-design; EC.
- Amplitude of low frequency fluctuation abnormalities in adolescents with online gaming addiction; EC.
- An analysis of player affect transitions in survival horror games; IC.
- An application framework for controlling an avatar in a desktop-based virtual environment via a software SSVEP brain-computer interface; EC.
- An audio game app using interactive movement bonification for targeted posture control; EC.
- An EEG-based approach for left-handedness detection; EC.
- An effective neurofeedback intervention to improve social interactions in children with autism spectrum disorder; EC.
- An exploratory study of learners' brain states; EC.
- An virtual vehicle control game for online brain computer interface feedback training; EC.
- Analysis of brainwave characteristics for playing heterogeneous computer games; EC.
- Analysis of computer game player stress level using EEG data; EC.
- Analysis of EEG signals regularity in adults during video game play in 2D and 3D; EC.

Anticipatory EEG signals for detecting and classifying game interaction onset; IC.

Application of hybrid BCI and exergames for balance rehabilitation after stroke; EC.

Applications of modern HCIs in adaptive mobile learning; EC.

Applying a brain-computer interface to support motor imagery practice in people with stroke for upper limb recovery: A feasibility study; EC.

Are low cost brain computer interface headsets ready for motor imagery applications?; EC.

Are we there yet? Evaluating commercial grade brain-computer interface for control of computer applications by individuals with cerebral palsy; NA.

Art behind the mind: Exploring new art forms by implementation of the electroencephalography; QC.

Assessing NeuroSky's usability to detect attention levels in an assessment exercise; EC.

Assessment of learners' attention while overcoming errors and obstacles: An empirical study; EC.

Assessment of learners' motivation during interactions with serious games: A study of some motivational strategies in food-force; EC.

Assessment of the postural control strategies used to play two Wii Fit? videogames; EC.

Association of autonomic nervous system and EEG scalp potential during playing 2D Grand Turismo 5; EC.

Asynchronous P300-based brain-computer interface to control a virtual environment: Initial tests on end users; EC.

Attention deficit hyperactivity disorder: Improving performance through brain-computer interface; EC.

Attention training game with aldebaran robotics NAO and brain-computer interface; NA.

Audio-visual and autogenic relaxation alter amplitude of alpha EEG band, causing improvements in mental work performance in athletes; EC.

Augmented brain computer interaction based on fog computing and linked data; EC.

Augmented control of an avatar using an SSVEP based BCI; EC.

B-C-invisibility power: Introducing optical camouflage based on mental activity in augmented reality; EC.

Background music matters: Why video games lead to increased aggressive behavior?; EC

Bacteria Hunt evaluating multi-paradigm BCI interaction; EC.

Bacteria Hunt: A multimodal, multiparadigm BCI game; EC.

BCI and motion capture technologies for rehabilitation based on videogames; QC.

BCI and physiological computing for computer games: Differences, similarities and intuitive control; EC.

BCI applications for the general population; NA.

BCI could make old two-player games even more fun: A proof of concept with "Connect Four"; EC

BCI Demographics II: How many (and what kinds of) people can use a high-frequency SSVEP BCI?; EC

BCI framework based on games to teach people with cognitive and motor limitations; EC.

BCI promises in emotional involvement in music and games; EC.

BCI-based neurorehabilitation and prediction system for stroke patients; EC.

BCIs in multimodal interaction and multitask environments: Theoretical issues and initial guidelines; EC.

Berlin brain-computer interface - The HCI communication channel for discovery; EC.

Better brain interfacing for the masses: Progress in event-related potential detection using commercial brain computer interfaces; EC.

Bi-directional imagined hand movement classification using low cost EEG-based BCI; IC.

Bio-reckoning: Perceptual user interface design for military training; EC.

Biofeedback and virtual environments; EC.

Biofeedback game design: Using direct and indirect physiological control to enhance game interaction; EC.

Biofeedback implementation in a video game environment; EC.

BioStories: Dynamic multimedia environments based on real-time audience emotion assessment; EC.

BMI: Lessons from tests with impaired users; EC.

Brain activities associated with gaming urge of online gaming addiction; EC.

Brain activity and desire for Internet video game play; EC.

Brain computer interface based 3D game for attention training and rehabilitation; EC.

Brain control headset for gamers; EC.

Brain controlled games: Concepts and classifiers; EC.

Brain games as a potential nonpharmaceutical alternative for the treatment of ADHD; EC.

Brain mobile interfacing (BMI) system embedded with wheelchair; EC.

Brain Painting: Usability testing according to the user-centered design in end users with severe motor paralysis; EC.

Brain-computer interface and its applications in cognitive training; EC.

Brain-computer interface based on steady-state visual evoked potentials; EC.

Brain-computer interface based stroke rehabilitation for hemiplegia; EC.

Brain-computer interface games: Towards a framework; EC.

Brain-computer interface technologies: From signal to action; EC.

Brain-computer interface using P300 and virtual reality: A gaming approach for treating ADHD; EC.

Brain-computer interface: Generic control interface for social interaction applications; EC.

Brain-computer interface: Next generation thought controlled distributed video game development platform; EC.

Brain-computer interfaces for HCI and games; EC.

Brain-computer interfaces for stroke rehabilitation: Evaluation of feedback and classification strategies in healthy users; EC.

Brain-computer interfaces, virtual reality, and videogames; EC.

Brain-computer interfaces: Beyond medical applications; EC.

Brain-computer interfaces: Proposal of a paradigm to increase output commands; EC.

Brain-controlled robot agent: An EEG-based eRobot agent; EC.

Brain-computer interface controlled gaming: Evaluation of usability by severely motor restricted end-users; EC.

Brain-computer interfacing: More than the sum of its parts; EC.

Brainbasher: A BCI game; EC.

BrainBasher: A multi-modal BCI game for research and demonstration; EC.

BrainGain: BCI for HCI and games; EC.

Bright ideas: A wearable interactive "Inventometer" (brainwave-based idea display); EC.

Bringing digital games to user research and user experience; EC.

Can brain computer interfaces become practical assistive devices in the community?; EC.

Can children with AD/HD learn relaxation and breathing techniques through biofeedback video games?; EC.

Can digital game-based learning be incorporated in Serbian primary school curricula's?; EC.

- Can we use a brain-computer interface and manipulate a mouse at the same time?; EC.
- Chill-Out: Relaxation training through respiratory biofeedback in a mobile casual game; EC.
- ChillFish: A respiration game for children with ADHD; EC.
- Chromatic SSVEP BCI paradigm targeting the higher frequency EEG responses; EC.
- Classification effects on motion-onset visual evoked potentials using commercially available video games; EC.
- Classification improvement and analysis of P300 responses with various inter-stimulus intervals in application to spatial visual brain-computer interface; EC.
- Classification of affective data to evaluate the level design in a role-playing videogame; IC.
- Classification of cognitive states of attention and relaxation using supervised learning algorithms; IC.
- Closed-loop rehabilitation of age-related cognitive disorders; EC.
- CogniMeter: EEG-based emotion, mental workload and stress visual monitoring; EC.
- Cognition assessment: A framework for episodic measurement; EC.
- Cognitive intervention protocol for age-related memory impairments; QC.
- Communication and control by listening: Toward optimal design of a two-class auditory streaming brain-computer interface; EC.
- Comparing expert driving behavior in real world and simulator contexts; IC.
- Comparison of brain activation in response to two dimensional and three dimensional on-line games; EC.
- Competing and collaborating brains: Multi-brain computer interfacing; EC.
- Complexity analysis of EEG data during rest state and visual stimulus; EC.
- Computer games for user engagement in attention deficit hyperactivity disorder (ADHD) monitoring and therapy; EC.
- Concentration monitoring with high accuracy but low cost EEG device; EC.
- Conceptual priming for in-game BCI training; EC.
- Control of a wheelchair simulator in a three-dimensional environment using eye blink detection through non-invasive brain-computer interface; EC.
- Controlling a tactile ERP-BCI in a dual task; EC.
- Cooperative game play with avatars and agents: Differences in brain activity and the experience of play; IC.
- Correlation between videogame mechanics and executive functions through EEG analysis; IC.
- Cross benefits between virtual reality and games; EC.
- Decoding covert motivations of free riding and cooperation from multi-feature pattern analysis of EEG signals; EC.
- Decoding human motor activity from EEG single trials for a discrete two-dimensional cursor control; EC.
- Defecting or not defecting: How to "read" human behavior during cooperative games by EEG measurements; EC.
- Design a brain computer interface gaming system using steady-state visual evoked potential; EC.
- Design and application of brain computer interface auxiliary game platform based on motor imagery; NA.
- Design and implement of BCI system based on Android platform; EC.
- Design and implement of pocket PC game based on brain-computer interface; EC.
- Design and implementation of serious games for training and education; EC.
- Design of an asynchronous brain-computer interface for control of a virtual avatar; EC.

- Design on the control system of a Gait rehabilitation training robot based on brain-computer interface and virtual reality technology; QC.
- Designing a serious game for in-field interventions to promote nightlife well-being; EC.
- Designing affective video games to support the social-emotional development of teenagers with autism spectrum disorders; EC.
- Designing for engaging BCI training: A Jigsaw Puzzle; EC.
- Designing immersive affective environments with biofeedback; EC.
- Designing players' emotional reaction models: A generic method towards adaptive affective gaming; EC.
- Detecting stress using eye blinks during game playing; EC.
- Development and evaluation of an interactive electro-encephalogram-based neurofeedback system for training attention and attention defects in children; NA.
- Development and evaluation of low cost game-based balance rehabilitation tool using the Microsoft Kinect sensor; EC.
- Development of a biofeedback enhanced multimedia game; EC.
- Development of a low-cost BCI application using NeuroSky Mindband and Lego Mindstorms; NA.
- Development of a low-cost SVM-based spontaneous brain-computer interface; NA.
- Development of a simulated living-environment platform: Design of BCI assistive software and modeling of a virtual dwelling place; EC.
- Development of a wearable motion capture suit and virtual reality biofeedback system for the instruction and analysis of sports rehabilitation exercises; EC.
- Development of an exergame for individual rehabilitation of patients with cardiovascular diseases; EC.
- Development of an interactive game-based rehabilitation tool for dynamic balance training; EC.
- Development of Arduino based low cost neuro-feedback applied to ADHD; EC.
- Development of BCI based softwares to assist people with mobility limitations in the school inclusion process; QC.
- Development of computer games for assessment and training in post-stroke arm telerehabilitation; EC.
- Development of tactile biofeedback system for amplifying horror experience; EC.
- Development of the EEG measurement method under exercising; EC.
- Development of the game for increasing intensive power using EEG signal; EC.
- Different slopes for different folks: Alpha and delta EEG power predict subsequent video game learning rate and improvements in cognitive control tasks; EC.
- Disparity in brain dynamics for video games played on small and large displays; EC.
- Distinguishing difficulty levels with non-invasive brain activity measurements; EC.
- Dodging stress with a personalized biofeedback game; EC.
- Double-blind single-session neurofeedback training in upper-alpha for cognitive enhancement of healthy subjects; EC.
- Dynamic difficulty adjustment in computer games through real-time anxiety-based affective feedback; EC.
- Dynamic game difficulty control by using EEG-based emotion recognition; EC.
- Dynamic motion artifact removal using inertial sensors for mobile BCI; EC.
- E-Learning using video game for ADHD children; NA.
- Earlier visual N1 latencies in expert video-game players: A temporal basis of enhanced visuospatial performance?; EC.

Easy-algorithm in detecting left/right eye movements for playing pinball; EC.

EEG assessment of surprise effects in serious games; IC.

EEG biofeedback; EC.

EEG classification of physiological conditions in 2D/3D environments using neural network; EC.

EEG correlates of video game experience and user profile in motor-imagery-based brain-computer interaction; EC.

EEG data driven animation and its application; EC.

EEG feature of guess the coin game of human-computer; EC.

EEG headset supporting mobility impaired gamers with game accessibility; EC.

EEG signal analysis for measuring the quality of virtual reality; EC.

EEG signal feature analysis of smartphone game user; IC.

EEG spatio-spectral mapping during video game play; EC.

EEG spectral analysis in serious gaming: An ad hoc experimental application; EC.

EEG topographical maps analysis for 2D and 3D video game play; EC.

EEG-based "serious" games design for medical applications; QC.

EEG-based "serious" games and monitoring tools for pain management; NA.

EEG-based brain-computer interface for emotional involvement in games through music; IC.

EEG-based continuous control of a game using a 3 channel motor imagery BCI: BCI game; EC.

EEG-based dominance level recognition for emotion-enabled interaction; EC.

EEG-based expert system using complexity measures and probability density function control in alpha sub-band; NA.

EEG-based online two-dimensional cursor control; EC.

EEG-based upper alpha neurofeedback training improves working memory performance; EC.

EEG-based upper-alpha neurofeedback for cognitive enhancement in major depressive disorder: A preliminary, uncontrolled study; EC.

EEG-enabled affective applications; QC.

EEG, HRV and psychological correlates while playing Bejeweled II: A randomized controlled study; EC.

Effectiveness of commodity BCI devices as means to control an immersive virtual environment; EC.

Effectiveness of subject specific instruction on mu-based brain-computer interface training; EC.

Effects of P300-based BCI use on reported presence in a virtual environment; EC.

Effects of performing two visual tasks on single-trial detection of event-related potentials; EC.

Effects of user mental state on EEG-BCI performance; EC.

Electroencephalogram and physiological signal analysis for assessing flow in games; EC.

Electroencephalographic assessment of player experience; EC.

Electroencephalography (EEG)-based brain-computer interface (BCI): A 2-D virtual wheelchair control based on event-related desynchronization/synchronization and state control; EC.

Electrophysiological correlates of high-level perception during spatial navigation; EC.

Embodiment in brain-computer interaction; EC.

Emerging technologies with potential for objectively evaluating speech recognition skills; EC.

EMG based biofeedback system using a virtual reality method; EC.

Emotion assessment from physiological signals for adaptation of game difficulty; EC.

Emotion assessment in game playing; NA.

Emotion-enabled EEG-based interaction; IC.

Empirical evaluation of the Emotiv EPOC BCI headset for the detection of mental actions; EC.

Employing affection in elderly healthcare serious games interventions; EC.

Engaging, non-invasive brain-computer interfaces (BCIs) for improving training effectiveness and enabling creative expression; EC.

Enhanced brain computer interface system using virtual reality for neurorehabilitation; EC.

Enhanced learning with Abacus and its analysis using BCI technology; QC.

Enhancing video games in real time with biofeedback data; QC.

Error-related potentials during continuous feedback: Using EEG to detect errors of different type and severity; EC.

Evaluating a brain-computer interface to categorise human emotional response; EC.

Evaluating a multi-player brain-computer interface game: Challenge versus co-experience; EC.

Evaluating EEG measures as a workload assessment in an operational video game setup; EC.

Evaluating engagement physiologically and knowledge retention subjectively through two different learning techniques; IC.

Evaluating the ChillFish biofeedback game with children with ADHD; EC.

Evaluating the effectiveness of using electroencephalogram power indices to measure visual fatigue; EC.

Evaluating the ergonomics of BCI devices for research and experimentation; EC.

Evaluating the impact of player experience in the design of a serious game for upper extremity stroke rehabilitation; EC.

Evaluating user experience in a selection based brain-computer interface game A comparative study; EC.

Evaluating user experience of actual and imagined movement in BCI gaming; NA.

Evaluating user experience with respect to user expectations in brain-computer interface games; EC.

Evaluation of an adaptive game that uses EEG measures validated during the design process as inputs to a biocybernetic loop; EC.

Evaluation of attention levels in a Tetris game using a brain computer interface; IC.

Evaluation of the Bremen SSVEP based BCI in real world conditions; EC.

Examining brain activity while playing computer games; EC.

Exploiting real-time EEG analysis for assessing flow in games; EC.

Exploring a physiological environment learning tool for encouraging continued deep relaxation; EC.

Exploring the effects of prior video-game experience on learner's motivation during interactions with HeapMotiv; EC.

Extensive video-game experience alters cortical networks for complex visuomotor transformations; EC.

Facial expression recognition teaching to preschoolers with autism: A natural user interface approach; EC.

Failure to utilize feedback causes decision-making deficits among excessive Internet gamers; EC.

Feasibility analysis and adaptive thresholding for mobile applications controlled by EEG signals; EC.

Feasibility of game-based electromyographic biofeedback for dysphagia rehabilitation; EC.

Feasibility of using Tetrax Biofeedback video games for balance training in patients with chronic hemiplegic stroke; EC.

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From Mobie to Neu: 3D animated contents controlled by a brain-computer interface; EC.

Frontal EEG asymmetry in the study of player experiences during competitive and cooperative dual play; EC.

Frontal EEG theta changes assess the training improvements of novices in flight simulation tasks; EC.

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Game-based BCI training: Interactive design for individuals with cerebral palsy; EC.

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Game-based peripheral biofeedback for stress assessment in children; EC.

Game-based, portable, upper extremity rehabilitation in chronic stroke; EC.

Game-changing opportunities for wireless personal healthcare and lifestyle; EC.

Game-like training to learn single switch operated neuroprosthetic control; EC.

Games as neurofeedback training for children with FASD; QC.

Games-based biofeedback training applications in rehabilitation and fall prevention; EC.

Gaming control using a wearable and wireless EEG-based brain-computer interface device with novel dry foam-based sensors; EC.

Gaming controlling via brain-computer interface using multiple physiological signals; EC.

Gaming, fitness, and relaxation; EC.

Generic brain-computer interface for social and human-computer interaction; EC.

Hangman BCI: An unsupervised adaptive self-paced brain-computer interface for playing games; EC.

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High resolution EEG hyperscanning during a card game; EC.

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How should the state of the brain be described?; EC.

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iMind: An alternative dialogue between viewers and artists; EC.

Immersion and affect in a brain-computer interface game; EC.

Immersive BCI with SSVEP in VR head-mounted display; EC.

Immersive virtual reality and affective computing for gaming, fear and anxiety management; EC.

Implementation of a 3-dimensional game for developing balanced brainwave; EC.

Improvement of neurofeedback therapy for improved attention through facilitation of brain activity using local sinusoidal extremely low frequency magnetic field exposure; EC.

Improving patient motivation in game development for motor deficit rehabilitation; EC.

Increased oscillatory theta activation evoked by violent digital game events; EC.

Independent component analysis of EEG recorded during two-person game playing; EC.

Indirect biofed architecture: Strategies to best utilise biofeedback tools and interaction metaphors within digital architectural environments; EC.

Individual alpha frequency (IAF) based quantitative EEG correlates of psychological stress; EC.

Individual theta/beta based algorithm for neurofeedback games to improve cognitive abilities; NA.

Indoor skydiving in immersive virtual reality with embedded storytelling; EC.

Influences of state and trait affect on behavior, feedback-related negativity, and P3b in the Ultimatum Game; EC.

Integrating biosignals into information systems: A NeuroIS tool for improving emotion regulation; EC.

Integration of assistive technologies into 3D simulations: An exploratory study; EC.

Integration of EEG-based brain computer interfaces in serious games; EC.

Interacting in 3D virtual worlds with brain computer interfaces; EC.

Interacting with multiple game genres using motion onset visual evoked potentials; EC.

Interactive entertainment, virtual motion training and brain ergonomics; EC.

Interactive neuro-educational technologies (I-NET): Development of a novel platform for neurogaming; EC.

Investigating a gaze-tracking brain computer interface concept using steady state visually evoked potentials; EC.

Investigating brain activation with respect to playing video games on large screens; EC.

Investigating the use of brain-computer interaction to facilitate creativity; EC.

Investigation on player and virtual environment interaction; IC.

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KAPEAN: Understanding affective states of children with ADHD; IC.

Keep your opponents close: Social context affects EEG and fEMG linkage in a turn-based computer game; EC.

Learning EEG-based spectral-spatial patterns for attention level measurement; EC.

Learning to multitask: Effects of video game practice on electrophysiological indices of attention and resource allocation; EC.

LewiSpace: An educational puzzle game combined with a multimodal machine learning environment; IC.

Lost in the dark: Emotion adaption; QC.

Low cost implementation of a motor imagery experiment with BCI system and its use in neurorehabilitation; IC.

Measuring emotion regulation with single dry electrode brain computer interface; EC.

Measuring enjoyment in games through electroencephalogram (EEG) signal analysis; EC.

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Monitoring cerebral processing of gustatory stimulation and perception using Emotiv Epoc; EC.

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Motor and attentional mechanisms involved in social interaction - Evidence from mu and alpha EEG suppression; EC.

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Motor imagery for severely motor-impaired patients: Evidence for brain-computer interfacing as superior control solution; EC.

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Multi-brain BCI: Characteristics and social interactions; EC.

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Multi-modal human-computer interfaces for handicapped user groups: Integrating mind and gaze; EC.

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NEDE: An open-source scripting suite for developing experiments in 3D virtual environments; EC.

Neu: How brain activity can change an animated scene; EC.

Neural mechanisms underlying the orienting response to subject's own name: An event-related potential study; EC.

Neural prosthetic asynchronous control using EEG; EC.

Neural strategies for selective attention distinguish fast-action video game players; EC.

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Neuronal correlates of a virtual-reality-based passive sensory P300 network; EC.

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Non-invasive brain-actuated interaction; EC.

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P300-based brain-computer interface memory game to improve motivation and performance; EC.

Perception and manipulation of game control; EC.

Perception of graphical virtual environments by blind users via sensory substitution; EC.

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Personality trait and facial expression filter-based brain-computer interface; EC.

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Playing Tetris with non-invasive BCI; EC.

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Playing with your mind; EC.

Please biofeed the zombies: Enhancing the gameplay and display of a horror game using biofeedback; EC.

Positive emotions associated with "Counter-Strike" game playing; EC.

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Rehabilitation of balance-impaired stroke patients through audio-visual biofeedback; EC.

RehabNet: A distributed architecture for motor and cognitive neuro-rehabilitation; IC.

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Relevant HCI for hybrid BCI and severely impaired patients; EC.

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Steady state visual evoked potential based computer gaming - The Maze; EC.

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Swallowing training combined with game-based biofeedback in Poststroke Dysphagia; EC.

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Target-shooting exergame with a hand gesture control; EC.

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The relationship between attention assessment and EEG control; EC.

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The user-centered design as novel perspective for evaluating the usability of BCI-controlled applications;

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Towards passive brain-computer interfaces: Applying brain-computer interface technology to human-machine systems in general; EC.

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- Using biofeedback while immersed in a stressful videogame increases the effectiveness of stress management skills in soldiers; EC.
- Using biometric measurement in real-time as a sympathetic system in computer games; EC.
- Using brain-computer interfaces to determine the location of missing people; EC.
- Using EEG pattern analysis for implementation of game interface; EC.
- Using electroencephalogram to track learner's reasoning in serious games; EC.
- Using electroencephalography and subjective self-assessment to measure the influence of quality variations in cloud gaming; EC.
- Using physiological signal analysis to design affective VR games; EC.
- Using scalp electrical biosignals to control an object by concentration and relaxation tasks: Design and evaluation; EC.
- Valence, arousal and dominance in the EEG during game play; EC.
- VALENCE: Affective visualisation using EEG; EC.
- Validation of the Emotiv EPOC EEG system for research quality auditory event-related potentials in children; EC.
- Validation of the Emotiv EPOC®EEG gaming system for measuring research quality auditory ERPs; EC.
- Vanishing scares: Biofeedback modulation of affective player experiences in a procedural horror game; EC.
- Video game training and the reward system; EC.
- Video game training enhances cognitive control in older adults; EC.
- Video games as a complementary therapy tool in mental disorders: PlayMancer, a European multicentre study; EC.
- Video games for neuro-cognitive optimization; EC.
- Videogame assisted emotional regulation training: An ACT with RAGE-control case illustration; EC.
- Virtual mindfulness meditation: Virtual reality and electroencephalography for health gamification; QC.
- Virtual reality game for memory skills enhancement based on QEEG; EC.
- Virtual reality interface devices in the reorganization of neural networks in the brain of patients with neurological diseases; EC.
- Water Ball Z: An augmented fighting game using water as tactile feedback; EC.
- Wiimote vs. controller: Electroencephalographic measurement of affective gameplay interaction; EC.
- Workload assessment of computer gaming using a single-stimulus event-related potential paradigm; EC.
- Zone of impulse: Physiological data enhanced gaming; EC.