Federal University of Parana

Luiza Maria Wille Culau

EEG applications: a literature review and game development

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Research presented as a partial requirement to the conclusion of the Undergraduate Degree in Computer Science, Exact Sciences sector, of the Federal University of Parana.

Field: *Computer Science*.

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Resumo

Interface cérebro computador (Brain Computer Interface, BCI) se refere a sistemas de comunicação em que as pessoas não interagem com o mundo por meio dos músculos ou nervos periféricos do corpo, mas sim com a atividade cerebral. Um dos sistemas BCI mais usados é através da eletroencefalografia (EEG), que mede a atividade elétrica do cérebro. Nesta pesquisa, o estado da arte das aplicações que utilizam a tecnologia EEG é investigado e, além disso, um jogo que usa um headset EEG é criado. Esta aplicação tem a intenção de permitir uma investigação sobre como as pessoas reagem a um jogo simples controlado por um headset EEG, tomando por consideração aspectos do campo de pesquisa de Interação Humano Computador. Dois experimentos foram feitos com 14 voluntários e estes experimentos deram um *insight* sobre como as pessoas percebem esse tipo de aplicação: por mais que controlar o jogo com um headset EEG tenha sido mais difícil do que controlar um jogo com um teclado, o headset EEG adicionou mais divertimento e tornou o jogo mais interessante.

Palavras-chave: electroencefalografia, EEG, interface cérebro computador, interface cérebro máquina, interação humano computador, aplicações baseadas em EEG.

Abstract

Brain computer interface (BCI) refers to communication systems in which people do not interact with the world by the body's peripheral nerves and muscles, but rather with their brain activity. One of the most used BCI systems is via electroencephalography (EEG) technology, which measures the brain's electric activity. In this research, the state of the art of EEG technology based applications was investigated, furthermore, a gaming application using an EEG headset was developed. This application was intended to allow further investigations on how people react to a simple game controlled by an EEG headset, taking in consideration aspects of Human-Computer Interaction field of study. Two experiments were held with 14 volunteers and they gave an insight on how people perceive such applications: although controlling a game with the EEG headset is harder than controlling a game with a keyboard, the EEG headset added more fun and made the game more interesting.

Keywords: electroencephalography, EEG, brain computer interface, brain machine interface, human computer interaction, EEG based applications.

Contents

Acronyms List

HCI	Human-Computer Interaction
BCI	Brain-Computer Interface
EEG	Electroencephalography
UFPR	Federal University of Parana (Universidade Federal do Paraná)
RQ	Research Question
fMRI	Functional Magnetic Resonance Imaging
ECoG	Electrocorticography
MEG	Magnetoencephalography

Chapter 1

Introduction

For many decades, brain-computer interaction (BCI) technology has been intriguing people's imagination and even creating a certain fear of the future due to the thought process: "if the brain can control technology, could this interaction affect someone's brain or personality negatively?", as depicted in classic movies such as "Matrix" and, more recent, TV Shows such as "Sword Art Online". But what is the reality of such technologies, and what is actually possible with the current technology?

There are several different approaches for gathering brain activity data, from invasive modalities that require implanting microelectrode arrays inside a person's skull to less invasive modalities such as headsets equipped with electrodes. The main neuroimaging methods can be classified as invasive and non-invasive as well as portable and non-portable. The invasive methods, such as Electrocorticography (ECoG) and Intracortical neuron recording, have the advantage of allowing more precise measurements (having higher temporal and spacial resolution), but the main disadvantage of offering health hazards as they require the implant of electrode grids on the surface of the brain (ECoG) or the implant of microelectrode arrays inside the cortex (Intracortical neuron recording) [Nicolas-Alonso and Gomez-Gil, 2012].

Some of the non-invasive approaches such as Magnetoencephalography (MEG) and Functional Magnetic Resonance Imaging (fMRI) are non portable, which makes them of hard use for applications that intend to increase the freedom of people with motor disabilities. MEG requires the equipment to be installed inside a magnetically shielded room and fMRI requires a bulky and expensive hardware.

Electroencephalography (EEG) is the most widespread modality since it is non-invasive, portable and signals are easily recorded by electrodes placed on the scalp. Another advantage of EEG is the possibility of using "dry" electrodes, which are electrodes that do not require a conductive gel, therefore allowing more comfort to the user.

The major disadvantage of EEG is that signals that can be recorded are of poor quality, since the brain signals pass by many layers before arriving outside the scalp. However, the EEG technology and headset architecture are still evolving, several companies are selling this technology, and a variety of headset designs, headset quality and headset materials can be obtained and integrated with an intended application.

1.1 Problem Formulation

The study of brain activity by placing electrodes on the surface of the skull dates back from 1875 when a British physiologist Richard Caton investigated the electrical activity of the brains of small animals. It was only in 1929 that the first study of electroencephalogram done on humans was published by the German psychiatrist Hans Berger [Cooper et al., 2014].

Nowadays there are EEG-based studies all over the world, involving stakeholders from a variety of economical backgrounds, cultures, research areas and ages. However, are there any excluded groups of people as target audience? What is the growth rate of such technologies in the last 10 years[1]? Can the EEG-based applications still be improved? How hard is it to develop such an application? In order to answer those questions a set of goals and solutions is proposed.

1.2 Proposed Solution and Goals

A state-of-the-art study of EEG applications done by systematic mapping of papers on the area is used to assist in the discussions cited above (in the Section 1.1) in Chapter 3. Afterwards, an application was developed and tested in Chapter 4, accompanied by a discussion in Chapter 5. For those who would like to start developing an application with an Emotiv EEG headset, there is a tutorial with a step-by-step on "How to EEG with Emotiv headset" in Chapter 6. The overall conclusion and future work discussion is shown in the Chapter 7.

[1]This research was made on papers and studies dating from 2007 to 2017

Chapter 2

Theoretical Background

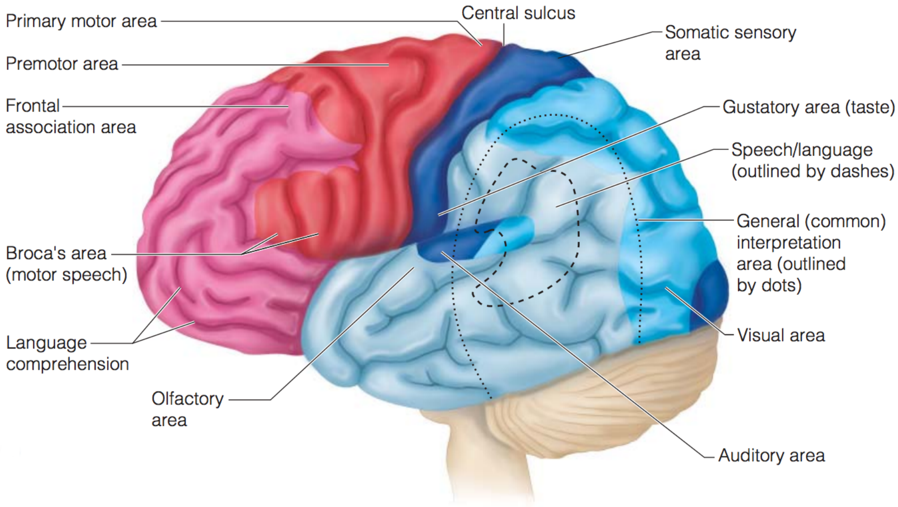
In this chapter you can learn and understand some of the key concepts and science behind EEG headsets and their functioning.

2.1 Brain Regions and Meaning

According to the book “Functional Neuroanatomy" [Machado, 1998], the first time scientists proved that the cortical area of the brain was not homogeneous was in 1861 when the french surgeon Pierre Paul Broca correlated lesions in restricted areas of the frontal lobe with the loss of speech. After that, many scientists continued studying the areas of the brain, finding out, for example, that stimulating certain areas of the brain made certain muscles move.

In 1949, Walter Hess was awarded the Nobel Prize of Medicine for finding connections between function and localization in the brain. He experimented on cats, and found out that when certain regions of the brain were stimulated with electricity the cat would sleep, get defensive(and position itself as angry) or even evacuate (the intestine or bladder). Thanks to Heiss, the localization in the brain of various functions were mapped in detail [Olivecrona, 1949]. Figure 2.1 shows some of the brain regions and what physical or emotion functions they are related to.

Figure 2.1: Some brain regions and their functions [Marieb, 2005]



2.2 EEG and Brainwaves

EEG is a method to detect and monitor the electric activity in the brain. It is almost always non-invasive, which means no surgical procedure or body modification need to be done in order to use this method. The electroencephalogram electrodes are placed over the scalp, following internationally recognized placement standards. The most used and cited positioning system is called the “10/20 system”. This system was developed to standardize testing worldwide making it possible to compare studies from different countries. The meaning of "10" and "20" is that the distances between adjacent electrodes are either 10% or 20% of the total front–back or right–left distance of the skull [Wikipedia, 2018].

There are many different neural oscillations (brainwaves) occurring in the brain that can be detected by EEG electrodes. The first discovered and most widely investigated are called “alpha” waves (with frequency between 7.5 and 12.5 Hz). The alpha waves are also known by “Berger” waves in memory of the scientist who founded EEG and discovered those waves, Hans Berger. The different brain waves are associated with certain brain/motor actions, for example, alpha waves are more present when someone is relaxed and has his eyes closed.

This knowledge of different brain waves together with the knowledge of the brain regions and their function allowed engineers and computer scientists to develop a wide variety of EEG headsets that can detect and interpret a variety of emotions and muscle movements.

2.3 EEG Headsets

Since the discovery of brainwaves and EEG technology, the manner by which the brainwaves are read has changed a lot. In the past, only wet electrodes (electrodes that need some conductive gel to be able to read data) were available. Nowadays due to the invention of dry electrodes, the electrodes have become more user-friendly and less cumbersome to use. Instead of placing separate electrodes on the scalp one by one, many companies worldwide have developed EEG devices that unite the electrodes into one single headset that is easy to place on people’s head and is adjustable.

Each headset model is unique on it’s design, number of channels (when an electrode captures brainwaves it’s called a channel), placement of electrodes and, therefore, each headset is able to interpret different mental states that have different precision. The number of channels vary from 1 (Neurosky headsets) up to 256 channels (BioSemi and ANT Neuro)[1].

Many brands of EEG headsets are easily available for people to buy online. The prices vary a lot, for example the NeuroSky Mindwave on Amazon now costs about \$79[2] while the Muse Headband costs about \$249[3] and the Emotiv EPOC+ costs \$799[4] (at the Emotiv’s online store). The choice of the best headset to use with an application will depend on what is going to be developed as well as price, comfort, and many other criteria such as quality and available programming tools. Some EEG headsets are easier for programmers to manage since some

[1]The interested reader can check out those headsets on the links: `https://www.biosemi.com/products.htm` and `https://www.ant-neuro.com/products/eego_mylab`

[2]Consulting date: 26/06/2018, link to the item: `https://www.amazon.com/NeuroSky-80013-001-MindWave-Headset/dp/B00A2UQUXY/ref=sr_1_1?ie=UTF8&qid=1530011005&sr=8-1&keywords=neurosky+mindwave`

[3]Consulting date: 26/06/2018, link to the item: `https://www.amazon.com/Muse-Brain-Sensing-Headband-Black/dp/B00LOQR37C/ref=sr_1_3?ie=UTF8&qid=1530011005&sr=8-3&keywords=neurosky+mindwave`

[4]Consulting date: 26/06/2018, link to the item: `https://www.emotiv.com/product/emotiv-epoc-14-channel-mobile-eeg/`

have APIs, examples and manuals and others do not. Some companies will allow headsets to communicate raw EEG data (data without any processing) and others will require an extra payment in order to do it. In short, many variables need to be taken into account before a researcher or developer buys a headset.

Chapter 3

Mapping of EEG Applications

Before designing and developing an application it is important to know what other applications were already created and what was their impact on the consumers. This knowledge would prevent the creation of applications that are already in the market and also prevent the development of applications that did not get well accepted by consumers. It is also important to know how were they made and what were some challenges faced upon the development of such applications in order for technical mistakes to be avoided in the future. The systematic mapping guide proposed by [Petersen et al., 2015] allows the understanding of the state of the art of the EEG headset technology usage. By following the guidelines of systematic mapping approach, the following research questions emerged.

3.1 Research Questions

- RQ1: What are the most common purposes for the applications using EEG headsets?
- RQ2: What are the applications' target audience? (for example: children, disabled people, adults, etc.)
- RQ3: For what environment were those applications developed? (University, home, industry, hospital, etc.)
- RQ4: What other elements/equipment/devices were used in the applications? (virtual reality headsets, robots, cell phones, micro-controller devices, etc.)
- RQ5: What EEG headsets have been used?
- RQ6: What can be interpreted from the EEG data (recorded by the headsets) with the applications?
- RQ7: What programming languages were used?
- RQ8: Were stakeholders involved in the process of research and development of the application? Who? How many? How?
- RQ9: In what educational institutions were the researches developed ? In what country are those institutions located?
- RQ10: What is the growing rate in the number of studies between 2007 and 2017?

3.2 Search Strategy

In order to answer the research questions, a set of search strings were used in three search bases: IEEEXplore, Springer and ACM Digital Library. All the search strings used respected and contained some of the following keywords: EEG, headset, electroencephalogram, project, application, brain computer, case study. The material gathered with the search was filtered by inclusion/exclusion criteria as shown in Table 3.1.

Inclusion criteria:
- Material must be about using the signals coming from EEG devices as input to application(s). Materials considered were: papers and articles.
Exclusion criteria:
- Material only about the study of the brain using EEG devices.
- Material only about tracking and studying sleep states.
- Material only about the development of EEG hardware (electrodes, headsets) and EEG headset performance.
- Material about interfaces or tools (such as servers) that can be paired with EEG headsets that are not final applications per se.
- Material in languages other than: Portuguese, English, French.
- Duplicated material. If a research was published several times with equal or different text, the most complete material is kept.
- Material published before 2007 or after 2017.
- Material that focuses on technology other than EEG for brain-computer interfaces.
- The study does not present an experiment with the use of EEG equipment.

Table 3.1: Inclusion/Exclusion criteria

IEEE Xplore

IEEE Xplore has tools to refine the search with the additional advantage of excluding research from totally different areas from Computer Science and Engineering areas. Therefore, a filter for results published only after “2007” was applied because of the exclusion criteria. The search was done using the “command search” tool looking for matches in the full text and the meta data, with the following search string:

IEEEX: *"EEG application" OR "EEG project" OR "electroencephalogram application" OR "electroencephalogram project" OR "brain computer EEG" OR "EEG brain computer" OR "EEG case study" OR "EEG headset"* [1]

[1]The search can be seen on the link: `https://ieeexplore.ieee.org/search/searchresult.jsp?queryText=(.QT.EEG%20application.QT.%20OR%20.QT.EEG%20project.QT.%20OR%20.QT.electroencephalogram%20application.QT.%20OR%20.QT.electroencephalogram%20project.QT.%20OR%20.QT.brain%20computer%20EEG.QT.%20OR%20.QT.EEG%20brain%20computer.QT.%20OR%20.QT.EEG%20case%20study.QT.%20OR%20.QT.EEG%20headset.QT.)&ranges=2007_2017_Year&matchBoolean=true&searchField=Search_All_Text` *Accessed in 26/06/2018*

SpringerLink

SpringerLink is another search tool that allows advanced search options, allowing to filter by date and language of the results. The following search string was used with the filter of date and language:

SL: *"EEG application" OR "EEG project" OR "electroencephalogram application" OR "electroencephalogram project" OR "brain computer EEG" OR "EEG brain computer" OR "EEG case study" OR "EEG headset"* [2]

ACM Digital Library

ACM DL showed less results than the other search engines since its focus is in the computer science area. Results were also filtered by date and the following search string was used:

ACM: *"EEG application" OR "EEG project" OR "electroencephalogram application" OR "electroencephalogram project" OR "brain computer EEG" OR "EEG brain computer" OR "EEG case study" OR "EEG headset"*[3]

3.3 Mapping Results and Analysis

In this section, the data extraction method is presented as well as the search results in the form of paragraphs or diagrams proceeded by an analysis of each diagram.

Before having applied the exclusion criteria and with the search strings above, a total of 801 studies were found using IEEEXplore, 427 studies were found using SpringerLink (including preview only studies) and 32 studies were found using ACM DL. After having applied the exclusion criteria, a total of 180 articles were cataloged from IEEEXplore, 18 from SpringerLink and 16 from ACM DL. Adding up, data from 214 articles was saved respecting the following template[4]:

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[2]The search can be seen on the link: `https://link.springer.com/search?date-facet-mode=between&facet-start-year=2007&facet-language=%22En%22&facet-end-year=2017&query=%22EEG+application%22+OR+%22EEG+project%22+OR+%22electroencephalogram+application%22+OR+%22electroencephalogram+project%22+OR+%22brain+computer+EEG%22+OR+%22EEG+brain+computer%22+OR+%22EEG+case+study%22+OR+%22EEG+headset%22&showAll=true` *Accessed in 26/06/2018*

[3]The search can be seen on the link: `https://dl.acm.org/results.cfm?query=%22EEG%20application%22%20OR%20%22EEG%20project%22%20OR%20%22electroencephalogram%20application%22%20OR%20%22electroencephalogram%20project%22%20OR%20%22brain%20computer%20EEG%22%20OR%20%22EEG%20brain%20computer%22%20OR%20%22EEG%20case%20study%22%20OR%20%22EEG%20headset%22&filtered=&within=owners%2Eowner%3DHOSTED&dte=2018&bfr=&srt=_score` *Accessed in 26/06/2018*

[4]The gathered data from the 214 articles can be downloaded from GitHub on the link `https://github.com/lumizila/MindInfinity-EEG/blob/master/GatheredData.xlsx` *Accessed in 26/06/2018*

Item	Value	Research Question
Study ID	Integer	
Paper title	Name of the article	
Author name(s)	Names of the authors	
Publication year	Calendar year	RQ10
Institution	Educational institution(s) in which the research was performed	RQ9
Country	Country(s) of the Institution(s) the research took place	RQ9
URL	Web address for accessing the paper	
Search engine	Search engine(s) where the Material was found	
App. general purpose	The application's main purpose	RQ1, RQ3
App. target's audience	To whom was the application developed for	RQ2, RQ8
App. collaborators	What organizations/individuals were involved in the development of the application	RQ8
Programming language used	The programming languages used to develop the application	RQ7
Necessary equipment	Other equipments necessary to develop the application	RQ4
EEG headset used	The name of the brand of the EGG headset or the responsible developers of the headset	RQ5
EEG headset read potential	What can the headset read and interpret from brain activity	RQ6
Participation of target audience	Were the stakeholders involved in the process of creation? When and how many?	RQ8

Table 3.2: Data extraction template. By the authors.

3.3.1 Answering the Research Questions

In this section, the research questions previously proposed will be answered by analyzing the data extracted from the 214 total filtered articles.

RQ1: What are the most common purposes for the applications using EEG headsets?

The applications found in the studies that are related to health and quality of life improvement are definitely the most common ones using EEG technology. As noticed in the Figure 3.1, the most common purpose for the applications is in robot control: 33 articles on this topic. Among the applications on robot control, most are about assistive robots and controlling robotic arm/grip although there are some very interesting articles on empathetic robots (they detect human emotion from the EEG data and then act accordingly). There are some other papers on prosthesis (8 total papers) or exoskeletons (6 total) controlled by EEG commands sometimes paired with other types of input such as voice and eye tracking. Health monitoring, diagnosis and even treatment had a total of 18 papers on it, and other 7 papers on seizure detection (that could have been added into the same category but I chose to leave it as a separate category since seizure detection is a very recurrent topic when dealing with EEG technology).

Under assistive technology, there are also several researches on wheelchair control (16 papers), often paired with other forms of input (eye tracking, voice recognition, fMRI, joystick). The applications for controlling wheelchairs were left as a separate category since it was a recurrent topic. Spelling or speech systems and other communication tools add up to 20 papers. "Speech system" is an example of communication tool, since EEG data is transformed into sounds like vowels and syllables and even though the research is still on very simple sounds, it makes us think of a future where thoughts could be directly translated to speech. Finally, applications that increase disabled people's quality of life and technology interaction appeared in 16 articles, including those for browser navigation and smartphone navigation (for making calls and navigating a menu).

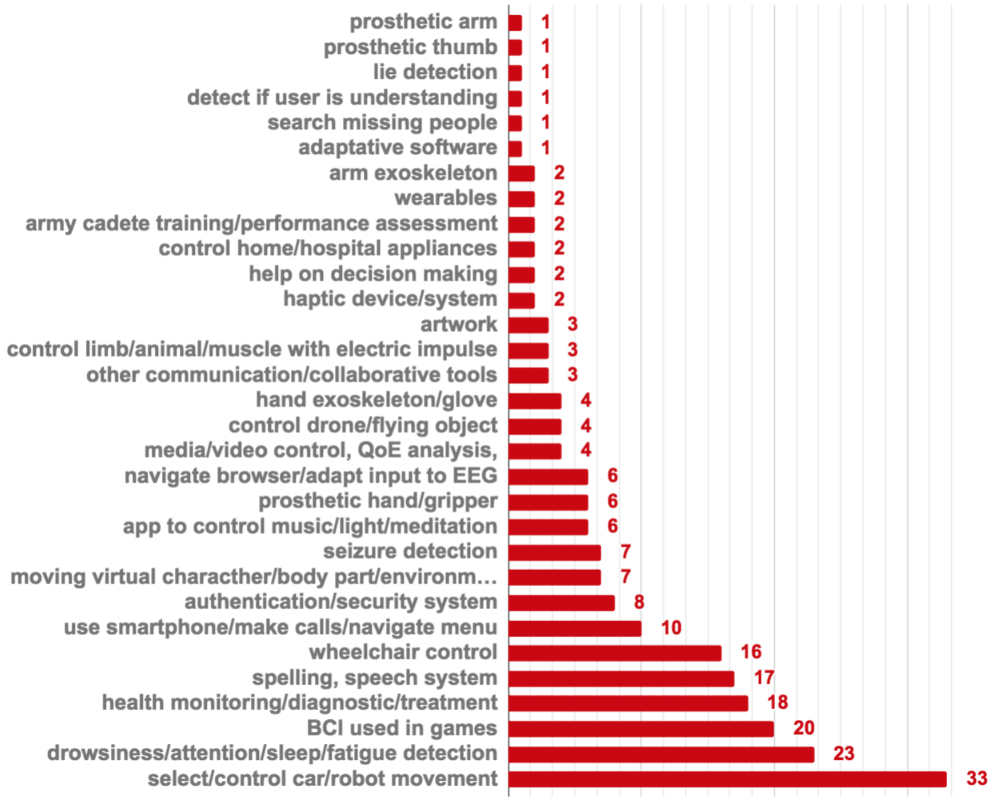

Figure 3.1: Applications' purposes. By the authors.

Drowsiness or fatigue detection applications were mostly applied on drivers to help accident prevention although some papers also included other professions that require a lot of concentration, such as surgeons and construction workers.

The category "BCI in games" includes 20 papers where EEG data is used to control a character or environment both in serious games and games for fun only. Some of the games were thought for disabled people, while some were developed for anyone so that people experience a new way of gaming. A lot of the EEG-based games were also paired with virtual reality headsets, making a very interesting and desired pairing since for the first time in people's lives being able to remain calm and control your thoughts can change a game dynamics.

Citing some specific papers regarding the Gaming field of study, there are several studies where EEG headsets were used to control characters or secondary game elements, with varying success. For example, researchers from the United Kingdom created a game for cultural heritage, where the main character is moved by a mix of cognitive functions and facial expressions [Vourvopoulos et al., 2012] read by an Emotiv EPOC headset. On another study, an Emotiv EPOC headset was used to perform some secondary tasks in the World of Warcraft game, such as abilities(skills) [van de Laar et al., 2013]. On both the studies, although performing tasks with the EEG headset did not bring a more efficient control of the game, the researchers concluded using the BCI made the game more interesting.

RQ2: What are the applications' target audience? (for example: children, disabled people, adults, etc.)

Since most EEG applications can be used by people with motor or speech disabilities one would assume they are the biggest target audience. In fact, most applications did not specify the target audience (see Figure 3.2), probably because many systems could be used by anyone. For

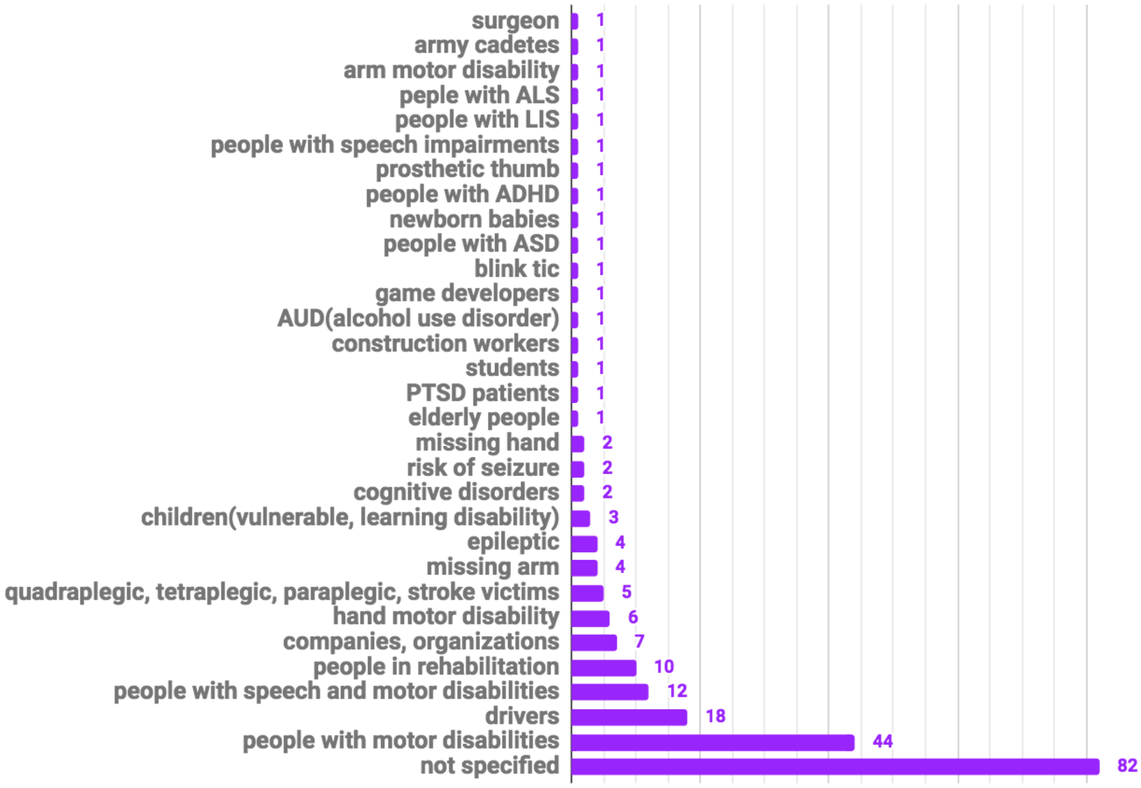

Figure 3.2: Applications target audience. By the authors.

example, a dialing system controlled by an EEG headset can be very useful for those people who are using their hands doing some other task, as a way of multitasking, although people with motor impairments would also benefit from such a dialing system. The same “multitasking" principle applies to brain controlled robots. If not a multitasking method, the EEG based applications open up a whole new way of human computer interaction, where a machine could not only be able to know what is the human command but also know how a human feels (tired, happy, sad, angry, etc.) at any moment.

One other common target audience benefit specially from the fact that EEG headsets allow monitoring and interpretation of brain activity, therefore it is also possible to detect and monitor brain activity anomalies as well as the progression/remission of diseases and disorders. People with alcohol use disorder (AUD), post traumatic stress disorder, attention deficit/hyperactivity disorder, autism spectrum disorder, epilepsy, locked-in syndrome, amyotrophic lateral sclerosis and blink tics are examples of target audience among the chosen papers in this study. EEG data has been used for diagnosis and even treatment of some of the disorders cited above, proving the huge potential of EEG based technology.

RQ3: For what environment were those applications developed? (For example: university, home, industry, hospital, etc.)

Most of the studies analyzed (154) did not have a specific target environment for the applications. Some of the studies mentioned where it *could* be used in the future, but the applications were not specifically thought for one or more environments.

As expected from the RQ2, some of the applications were thought to be used while driving (17). We could assume that the applications with the purpose of controlling a prosthesis

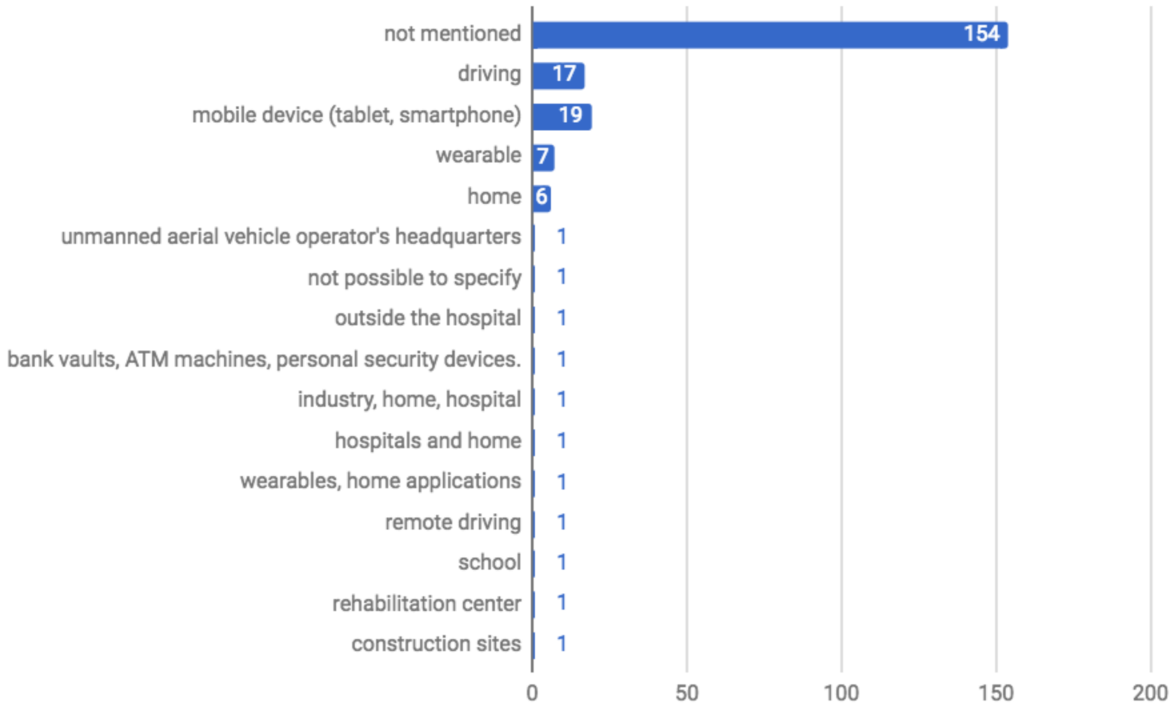

Figure 3.3: The target environments of the applications. By the authors.

or exoskeleton should be classified as "wearables," but most of them did not make it explicit which is why they were not all quantified in the Figure 3.3 as "wearable."

RQ4: What other elements/equipment/devices were used in the applications? (For example: virtual reality headsets, robots, cell phones, micro-controller devices, etc.)

As expected, computer and screens are the most used extra materials. Most of the EEG headsets do not have processing capacity to run programs, therefore a computer, smart-phone, micro-controller or tablet are needed. Figure 3.4 presents the most needed materials (besides the EEG headset or EEG electrodes).

A variety of electronic equipment appears in the cloud graph: from robots to prosthesis, VR headsets, flying devices, all of them represent very well the diversity of applications developed using EEG data.

RQ5: What EEG headsets have been used?

Emotiv's headset model "EPOC" (or the newest version of it called EPOC+) is by far the most popular among researchers (see Figure 3.5). Although not the cheapest of the headsets, Emotiv EPOC offers a lot of benefits because of the number of electrodes on it, allowing a deeper study of the brain and a more accurate input to applications when compared to other famous, more simple (and cheaper) headsets such as Neurosky Mindwave and Emotiv Insight.

Out of 214 studies, 34 mentioned making their own headsets using an EEG cap or using electrodes straight on the head of the person without making it a proper headset, specially earlier in time, when EEG headsets were not readily available in the market. Usually on those cases, the researchers would buy an EEG cap and electrodes, following international guidelines for positioning the electrodes. The problem about this approach is the limited mobility of the system, due to the lack of a wireless or Bluetooth communication between the electrode and the computer.

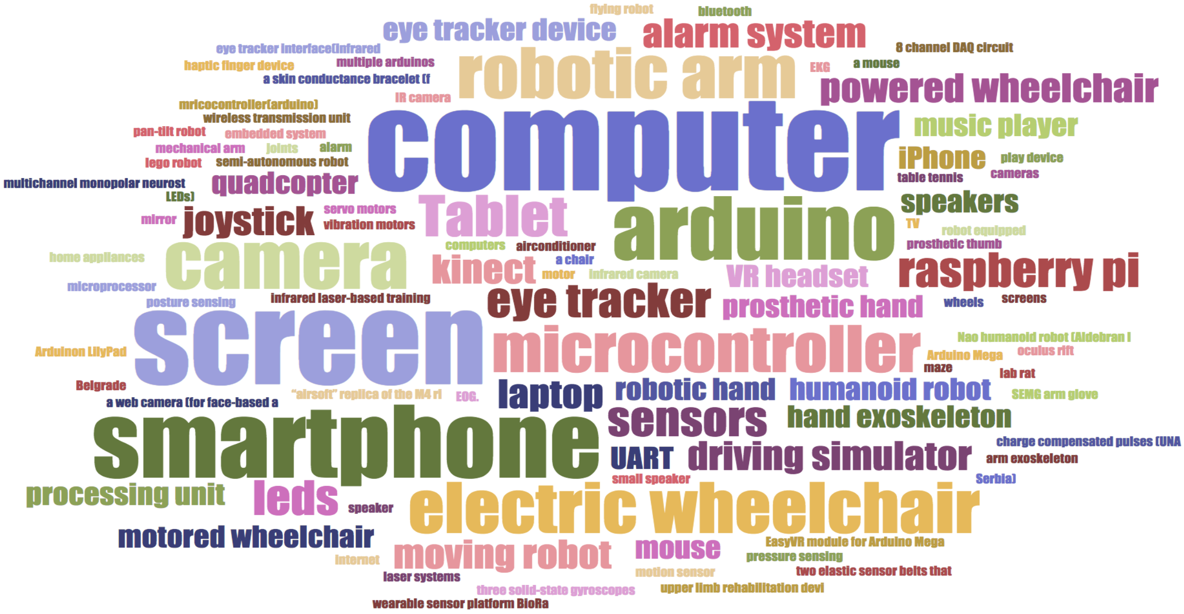

Figure 3.4: Complementary accessories. By the authors.

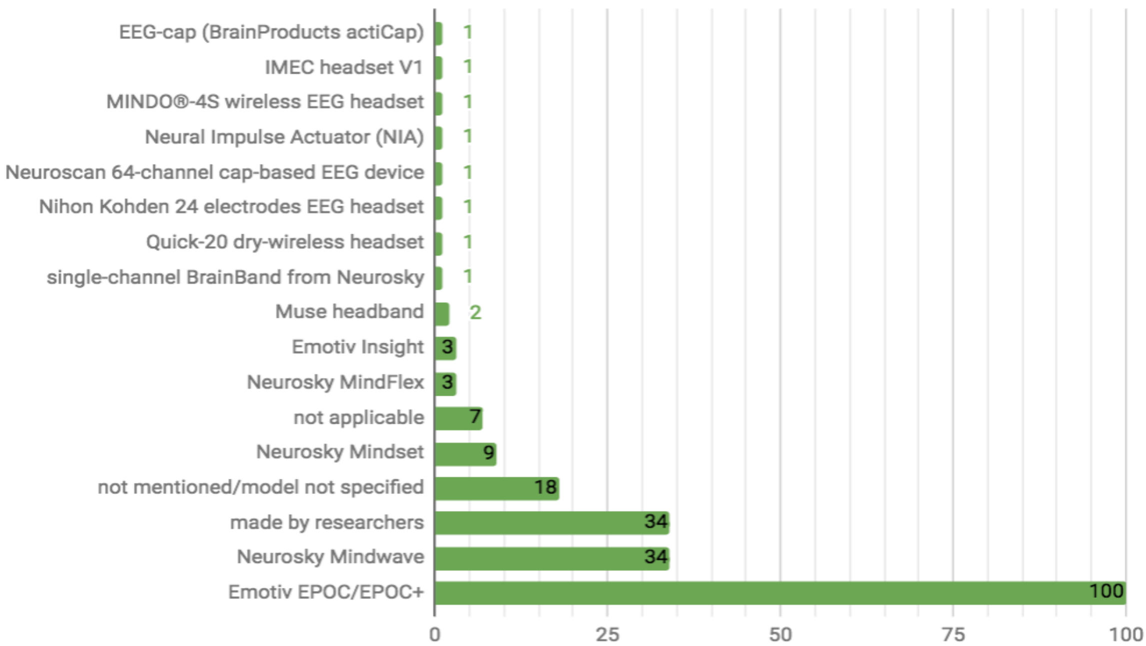

Figure 3.5: Main headsets used. By the authors.

Headset Name	Brand	Number of EEG sensors (excluding reference sensors)	Tools(API, SDK's)	Facial readings	Mental readings	Observations:
EPOC+	Emotiv	14	Cortex API, Cortex SDK	Blink Wink Left/Right Look Left/Right Furrow(frown) Raise brow(surprise) Smile Clench teeth(grimace) Laugh Smirk Left/Right	Excitement Long term excitement Frustration Engagement Relaxation Interest / Affinity Focus	
Insight	Emotiv	5	Cortex API, Cortex SDK	Blink Wink Left/Right Furrow (frown) Raise brow(surprise) Smile Clench teeth(grimace)	Excitement Long term excitement Stress Engagement Relaxation Interest / Affinity Focus	
Mindwave, Mindflex and Mindset	Neurosky	1	NeuroSky's Developer Tools (API's and software tools)	Eye blinks	Attention and Meditation	The Mindflex, Mindwave and Mindset headsets use the same chip.
Muse headband	Muse	4	Muse SDK, MuseIO	Blink Jaw clench	Concentration Mellow	

Figure 3.6: EEG headsets comparison. By the authors.

The studies classified as “not applicable” used a data set which was previously collected (not in the research period or by unrelated researchers), for developing and testing purposes.

RQ6: What can be interpreted from the EEG data (recorded by the headset) with the applications?

What can be interpreted from the EEG data mostly depends on where the electrodes are placed, since each region of the brain accounts for different emotions, thoughts, etc. The Figure 3.6 shows a comparison of some aspects of the 6 most used EEG headsets according to the 214 studies filtered.

A more detailed explanation is given below for the 5 most cited headsets: Emotiv EPOC/EPOC+, Neurosky Mindwave, NeuroSky Mindset, Neurosky MindFlex and Emotiv Insight.

- Emotiv EPOC/EPOC+

  According to the Emotiv’s webpage[5], this headset can interpret the following facial expressions: Blink; Left wink; Right wink; Furrow (frown); Raise brow (surprise); Smile; Clench teeth (grimace); Glance left; Glance right; Laugh; Smirk (left side); Smirk (right side). Also, it can interpret the following emotional states: Instantaneous excitement; Long term excitement; Frustration; Engagement; Meditation; Interest / Affinity; As for mental commands, it can detect the mental command “Neutral” and any of up to 4 pretrained items from a list of 13 labels: Push; Pull; Lift; Drop; Left; Right; Rotate clockwise; Rotate anti-clockwise; Rotate forwards; Rotate backwards; Rotate left; Rotate right; Disappear.

- Neurosky Mindwave

[5] `https://www.emotiv.com/comparison/`

Figure 3.7: The Minflex game by Mattel. Image found on 27/06/2018 at: https://en.wikipedia.org/wiki/NeuroSky

According to Neurosky's webpage[6] on this headset, it can measure and output the EEG power spectrums (alpha waves, beta waves, etc), the mental states of attention and meditation and eye blinks. The MindWave uses radio frequency (RF) to transmit data.

- Neurosky Mindset

  According to the 2009's instruction manual of this headset, " The MindSet reports the wearer's mental state in the form of NeuroSky's proprietary Attention and Meditation eSense™ algorithms, along with raw wave and information about the brainwave frequency bands"[7]. The MindSet headset uses Bluetooth to transmit data, it also includes Bluetooth stereo audio input and has a microphone.

- NeuroSky Mindflex

  The Mindflex headset and game were produced in by Neurosky in conjuntion with Mattel and released in 2009 as a toy. Using a fan and the EEG data a person is able to move a ball through obstacles on a course. The level of concentration is measured to control the fan that is moved around by a dial. See Figure where a person is playing the game 3.7[8].

- Emotiv Insight

  According to the Emotiv's webpage[9], this headset can interpret the following facial expressions: Blink, Left wink, Right wink, Furrow (frown), Raise brow (surprise), Smile, Clench teeth (grimace). Also it can interpret the following emotional states: Instantaneous

[6] `https://store.neurosky.com/pages/mindwave`

[7] To learn more about Mindset: `http://download.neurosky.com/support_page_files/MindSet/docs/mindset_instruction_manual.pdf`

[8] Image found in the link: `https://pt.aliexpress.com/item/Free-shipping-Hot-sale-New-Intelligence-toys-brainwave-mind-control-game-Mindflex-Duel-Game/1587160409.html`

[9] `https://www.emotiv.com/comparison/`

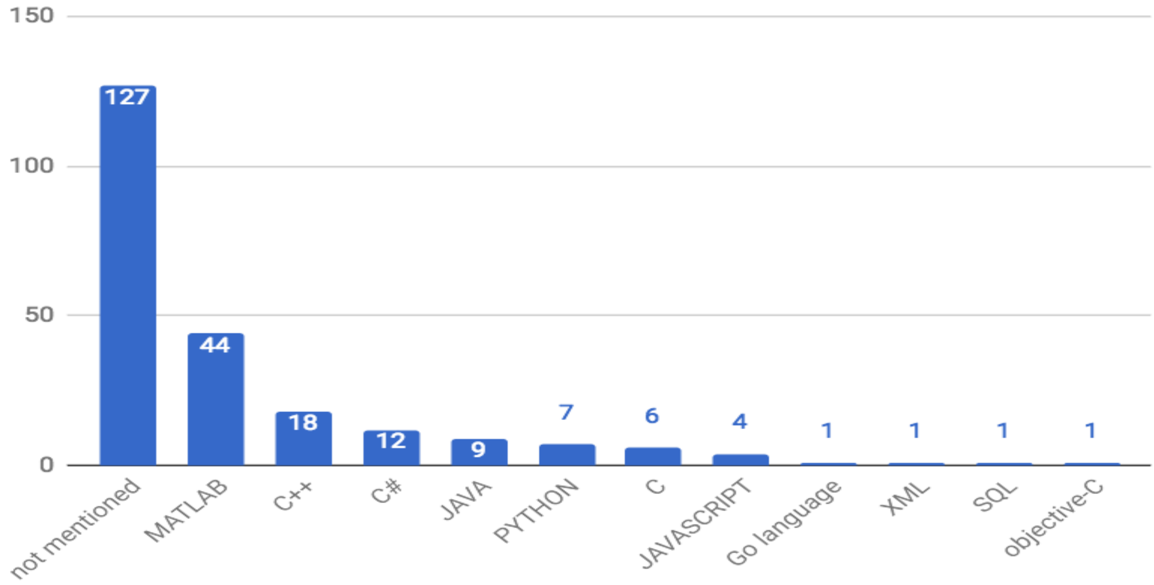

Figure 3.8: Graph showing the programming languages most used in the researches. By the authors.

excitement, Long term excitement, Stress, Engagement, Relaxation , Interest / Affinity, Focus. As for mental commands, it can detect the mental command "Neutral" and any of up to 4 pretrained items from a list of 13 labels: Push; Pull; Lift; Drop; Left; Right; Rotate clockwise; Rotate anti-clockwise; Rotate forwards; Rotate backwards; Rotate left; Rotate right; Disappear.

RQ7: What programming languages were used?

Although a lot of papers did not mention what programming languages were used to develop the applications (127 papers), it is possible that some of those papers used one of the following languages: Java, C#, C++, Python, Ruby, Node js, PHP. That assumption is based on the fact that most applications were developed to Emotiv EPOC/EPOC+ headsets and the languages above are the ones supported by the Emotiv Cortex API [10]. Matlab is the most cited programming language, since a lot of EEG data processing requires intensive mathematical operations to be performed.

RQ8: Were stakeholders involved in the process of research and development of the application? Who? How many? How?

A total of 142 articles mentioned involving people in the process of the development of the application; 60 did not mention involving people. Other 12 did not involve people in a direct way (for example, using datasets) which appears as "not applicable" in Figure 3.9.

RQ9: In what educational institutions were the researches developed? In what country are those institutions?

The number of researches on EEG applications was very well distributed among universities. The university with the biggest number of researches found was the Nanyang

[10]To learn more about the Emotiv Cortex API, you can visit the page https://github.com/emotiv/cortex-example

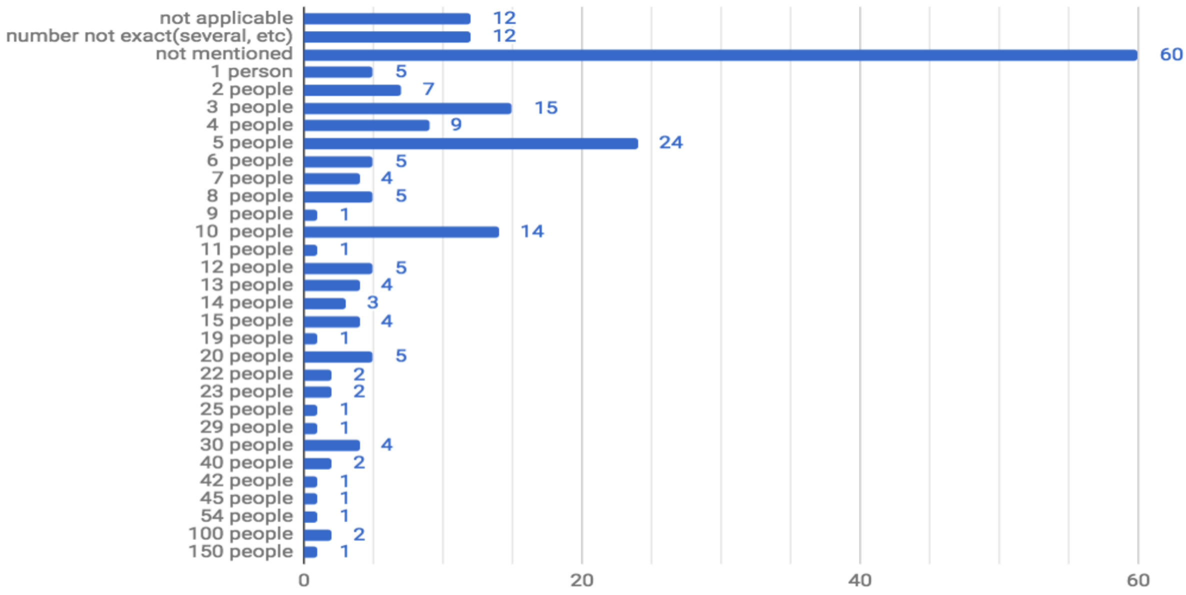

Figure 3.9: Graph showing how many people were involved in the researches. By the authors.

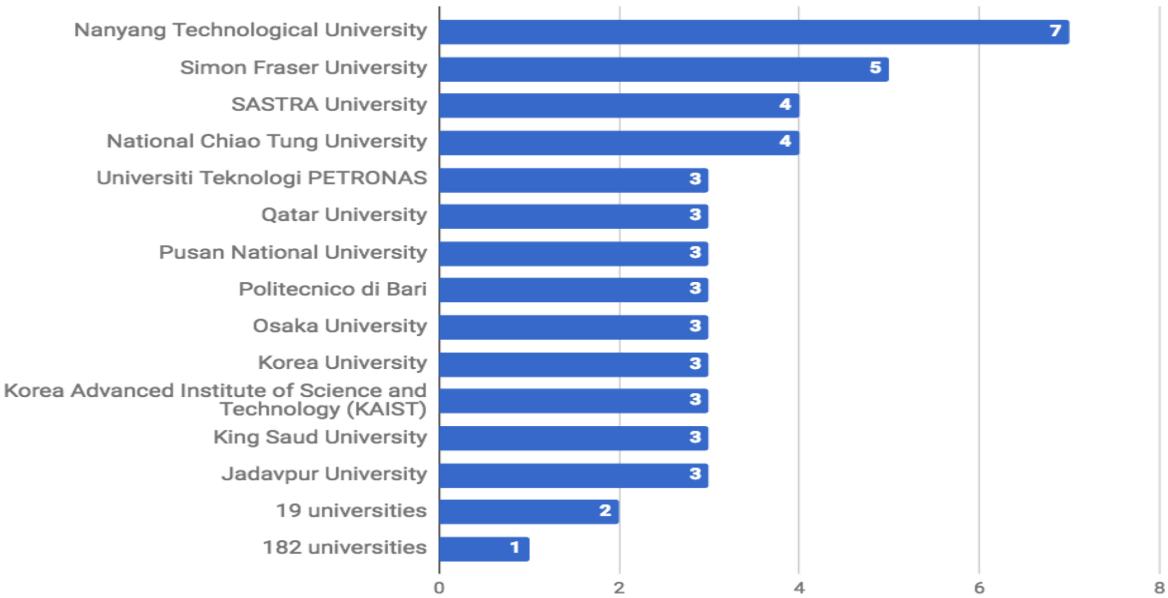

Figure 3.10: Main educational institutions involved in the researches and the number of papers published by those institutions. By the authors.

Technological University in Singapore with a total of 7 papers on the topic and the second university with most researches found was the Simon Fraser University in Canada with a total of 5 researches. See Figure 3.10 to see other universities.

Research was found belonging to countries in all of the continents (see Figure 3.11), but there are two major research concentrations in North America and Southeast Asia. See Figure 3.12 for a visual representation, where the more orange the more researches found done by universities in the country.

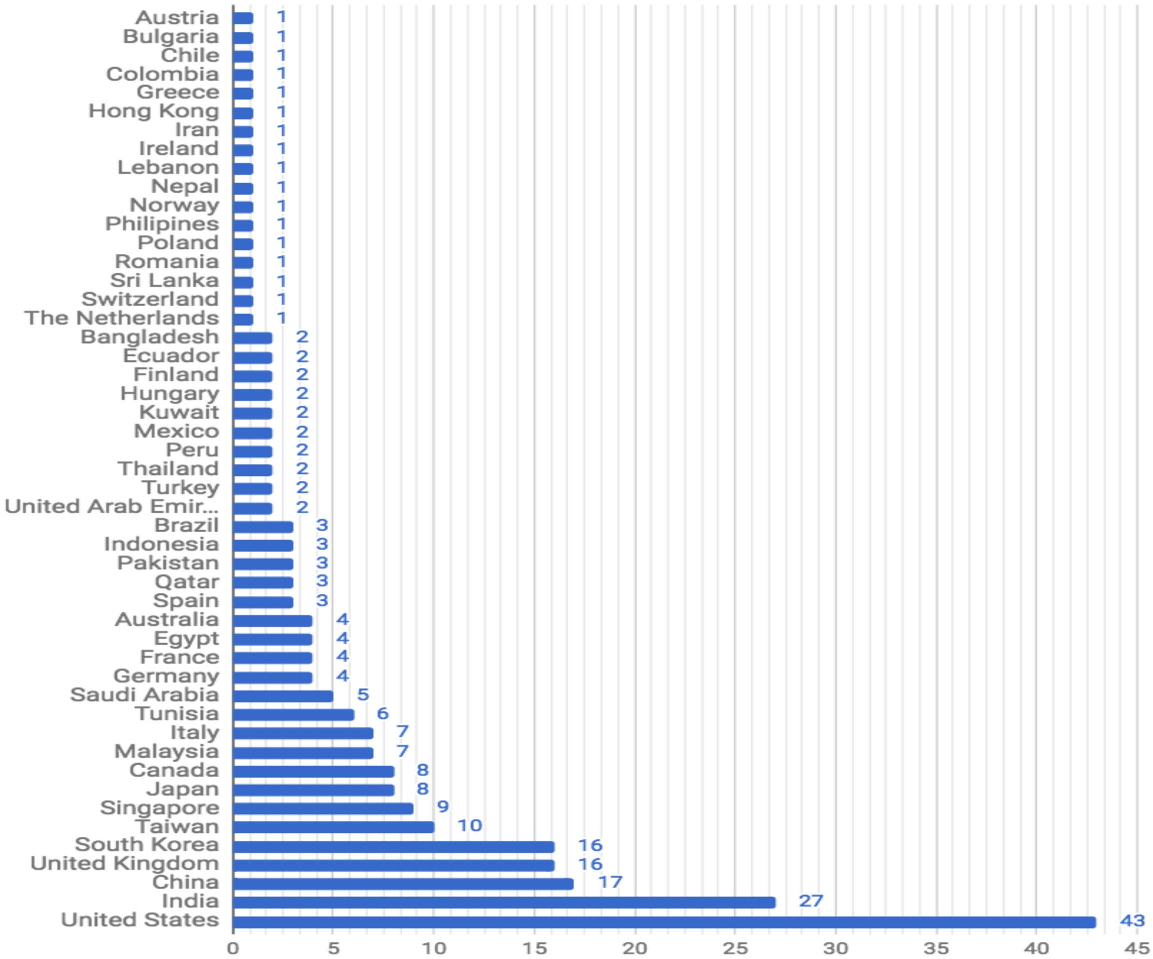

Figure 3.11: Countries where the researches were conducted. By the authors.

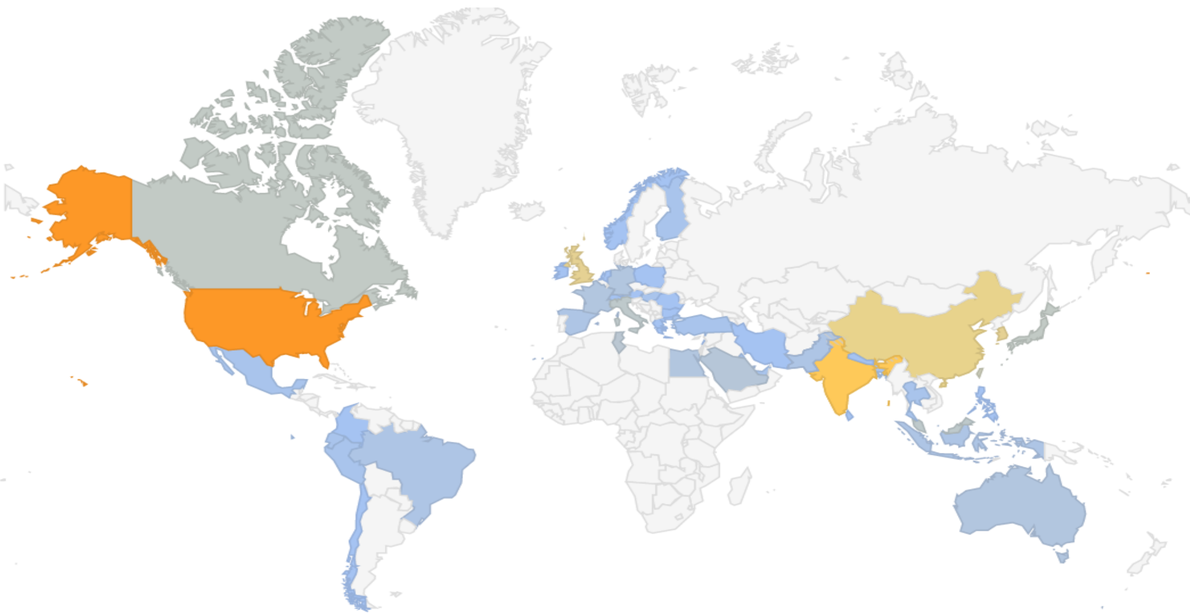

Figure 3.12: A heat map showing where the researches were made. The more orange a country is, the more researches were made there. By the authors.

RQ10: What is the growing rate in the number of studies between 2007 and 2017?

Based on the selected studies, a significant growth on the number of publications happened in 2013 and the number kept growing. The number was expected to decrease in 2017 as it was the current year when the search was performed and some of the studies were not published yet. Although few studies reporting applications involving EEG were published from 2007 to 2012, many other studies involved the development of the hardware part of EEG headsets. Those papers were not included in this graph because they did not match the inclusion criteria. The graph showing the exact number of selected papers by publication year is shown on the Figure 3.13.

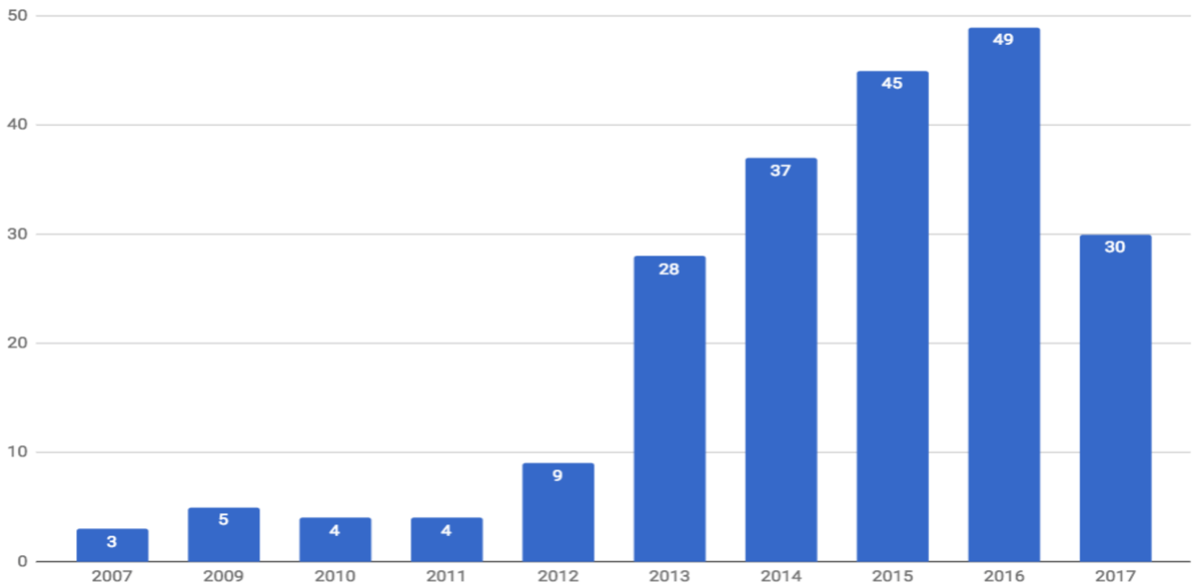

Figure 3.13: A graph showing the number of articles involving EEG applications between 2007 and 2017. By the authors.

3.4 Systematic Mapping Conclusion

An overall look on all the questions of the systematic mapping and their answers allows some reflections. There is a wide variety of researches on EEG applications, regarding the applications' purposes, target audience and extra accessories used in the applications. However, some target audiences such as children and elderly were cited on very few of the studies. This fact could be because a lot of the applications can be used by people of different ages. In any case, this also shows that there is still a lot of space for research and application development that involves the more excluded target audiences. With the growth on the number of the studies on EEG application in the past years, as well as the wide distribution of those studies in the whole world, it is likely that accessible EEG applications could become available to the consumers in the future.

Chapter 4

EEG Headset-based Application

In this chapter, a more detailed explanation of how the game application was developed is given. After that, a description of the game mechanics is given along with screen shots of the game itself.

4.1 Material, Hardware and Software

In order to develop the game application called MindInfinity, we used the programming language C# and Unity environment running on an OSx system to code. All the drawings and sounds of the game were also made by myself using the programs Gimp and Audacity. A library was also needed in order to make the connection with the headset, called “Websocketsharp”.

As for the hardware, a Macbook Pro to run the game, an Emotiv Insight to get EEG data and a USB receiver universal model to make the communication with the headset was used.

4.2 Development and Game Description

The development took about 2 months including the learning period, which included watching Unity tutorials and learning how to use the Emotiv’s Cortex API. Two versions of the game were made: the keyboard and the EEG version. In the EEG version, first the player chooses the language s/he wants to use, see Figure 4.1.

Afterwards, a table with the Emotiv devices detected is shown and the player chooses which device s/he wants to use, see Figure 4.2.

The next screen shows the quality of detection of each electrode, as well as hints to use the headset and the player can see himself/herself with the "webcam" image, see Figure 4.3.

Figure 4.1: First screen of the game. By the authors.

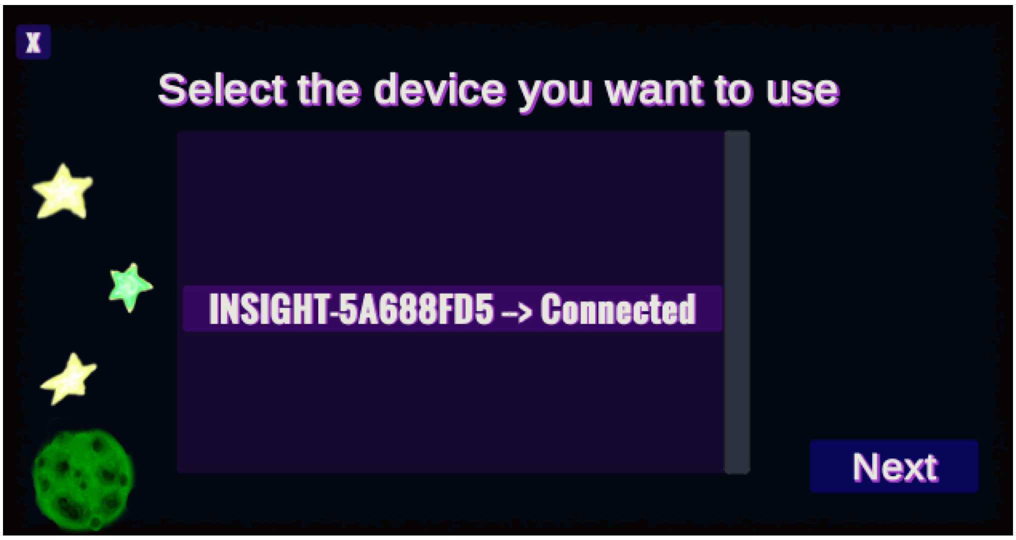

Figure 4.2: Second screen of the game. By the authors.

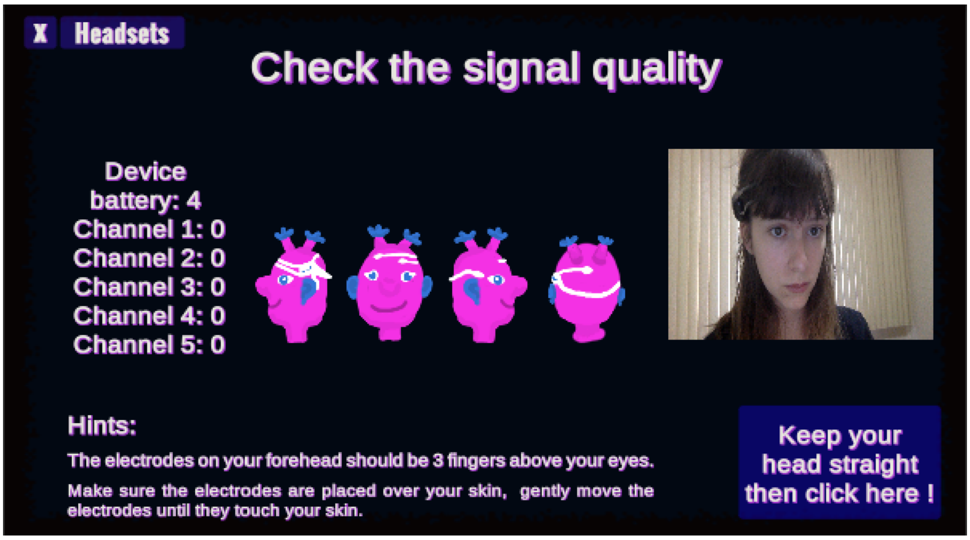

Figure 4.3: Third screen of the game. By the authors.

The spaceship is controlled by gyroscope data coming from the headset. When the player tilts his/her head to the right, the spaceship goes to the right (and the opposite when s/he tilts their head to the left). When the player tilts his/her head downwards the spaceship goes up and when the player tilts his head upwards, the spaceship goes down. The Figure 4.4 shows one moment of the game's training phase on the EEG version.

Figure 4.4: Fourth screen of the game. By the authors.

The player is then led to the game screen (see Figure 4.5), where the main goal is avoiding the asteroids (and therefore surviving in the game) for as long as possible. If the facial expression "frown" is detected by the EEG headset, the spaceship shoots 3 shots instead of 1 shot. The headset also detects the relaxation and stress mental states. Those mental states are used to change the color of the stars on the background, if the player is stressed the background will turn red, and if the player is relaxed the background will turn green. If the mental state is neutral, then the background stays as the default: yellow stars.

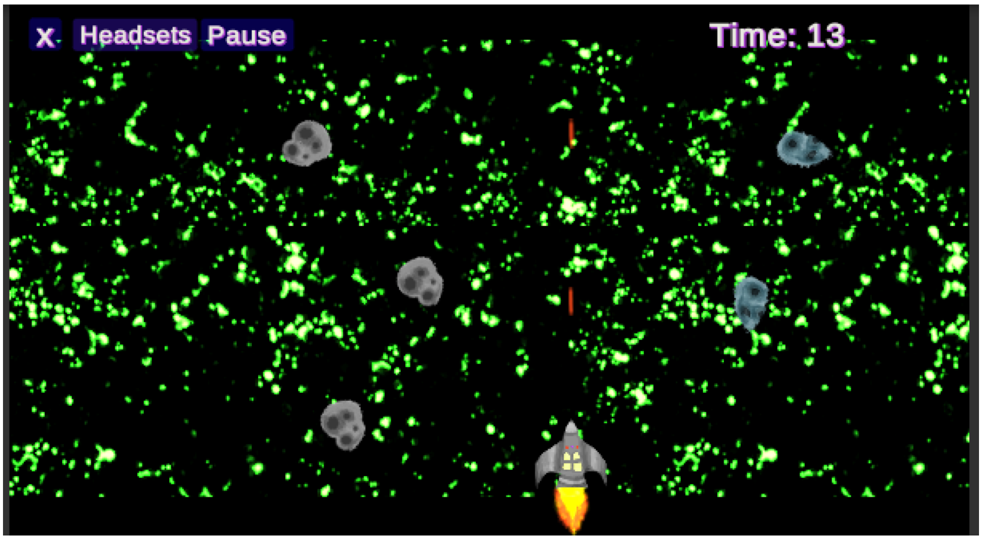

Figure 4.5: Fifth screen of the game. By the authors.

If a meteor hits the ship, it is game over and the player can see how long s/he survived for and choose to play again. See Figure 4.6.

Figure 4.6: Game over screen of the game. By the authors.

In the keyboard version, the player will also select the language first and then the very next page would be the training session's page. The player is instructed to use the arrow keys to move the ship, see this screen in Figure 4.7.

Figure 4.7: Training screen on the keyboard version of the game. By the authors.

After learning to move the ship the player reaches the next scene - the game scene. Here, just like before, the player has to avoid the ship being hit by asteroids to survive. If the player presses “space” button the ship will shoot 3 shots instead of only 1. If an asteroid hits the ship it will be game over to the player and s/he has the option to play again if s/he wants to.

4.3 Experiments with the game “MindInfinity”

The goal of the experiments is to help understanding the Emotiv Insight usage and what are its limitations. With that in mind, in this section we seek to answer the following questions:

- Q1: From the perspective of users, what are the biggest limitations/difficulties when using the Emotiv Insight?
- Q2: How satisfied are the users with this form of interaction?
- Q3: What can be done in the system to help the understanding and usage of the EEG device?
- Q4: What is the learning curve of the EEG headset’s usage to perform the tasks in the system?

4.3.1 Method and Dynamics

Fourteen people participated in this study, separated into two different experiments and none of the volunteers had used an EEG headset before.

Experiment 1

For the first experiment, four people were presented with the 2 versions of the game: the first version uses the Emotiv Insight headset as a game controller and the second version uses only the keyboard as a controller. The experiment was divided into 4 stages:

1. Training with Emotiv Insight
2. Playing using the Emotiv Insight
3. Training with the keyboard
4. Playing using the keyboard

In the "training" parts, the participant had some minutes to prepare and understand how to control the elements of the application (wearing the headset or using keyboard, navigating the game's menu and playing the tutorial).

In the "playing" parts, the participant played the actual game twice (until game over). The time of survival was recorded on both plays. After the participant finished playing with both the EEG headset and the keyboard, s/he completed an online questionnaire.

Experiment 2

Ten people were presented only with the game version that uses the Emotiv Insight headset as a game controller.

This experiment was divided into 2 parts: training and playing with Emotiv Insight. In the "training" part the participant had some minutes to prepare and understand how to control the elements of the application (wearing the headset, navigating the game's menu and playing the tutorial).

In the "gaming" part, the player played the game twice (until game over). The time of survival was recorded on both plays. After the second play, the participant completed a questionnaire, with fewer questions than the one applied to the first experiment.

4.3.2 The Questionnaires

The questions posed to the participants of this study were based on the Technology Acceptance Model (TAM). This model tries to explain why people accept and use technology and was developed by Fred Davis [Davis, 1989]. The TAM validated scales for two variables:

- Perceived usefulness (PU): how much does someone think a certain technology will be useful to complete certain tasks in a better way than before [Davis, 1989].
- Perceived ease of use (PEU): How easy does someone learn how to use a certain technology and how much effort they think it takes to use a certain technology [Davis, 1989].

Questions were divided into these two categories: perceived usefulness and perceived easy of use. The questions were adapted to a game technology in which the main objective is having fun. Therefore, usefulness here is understood by how much fun someone has playing the game on the second experiment.

The questionnaire used in the Experiment 1 had extra questions comparing the keyboard version and the EEG headset-based version of the MindInfinity game[1]. The questionnaire used in Experiment 2 had all the questions present in the questionnaire used in the Experiment 1 except

[1]The questionnaire used in Experiment 1 and the responses to it (in Brazilian Portuguese) can be seen completely in the link: `https://docs.google.com/forms/d/e/1FAIpQLSdqUfotFv11wqf85OdHyqsNrutNfODznbwnYAkoDz9z81LlxQ/viewform?usp=pp_url` *Accessed in 26/06/2018*

for those questions comparing the EEG and keyboard versions of the game, since the volunteers did not play the keyboard version of the game[2].

4.4 Results

In this section I present the results coming from the questionnaires filled by the participants. In the fist experiment, 3 participants were male and 1 female. One of them (volunteer number 2) reported having RSI (repetitive strain injury) in the hands that could have influenced on his/her result in the keyboard version of the game. In the second experiment, 8 participants were male and 2 female;

Figure 4.8 shows the number of answers to the questions asked on the questionnaires of both experiments. In the Figure, "GQ" stands for "General Question," PU stands for "Perceived Usefulness" and PEU stands for "Perceived Ease of Use."

Ref.	Affirmative	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
GQ1	"I like to play computer or console games"	0	0	0	3	11
GQ2	"I have experience with computer or console games"	0	0	1	4	9
	Perceived Usefulness					
PU2	"I believe the usage of the EEG headset made the game more fun"	0	0	2	3	9
PU5	"I believe the usage of the EEG headset made the game more interesting"	0	0	0	6	8
PU8	"I adored using the EEG headset to control the application!"	0	0	1	6	7
	Perceived Ease of Use					
PEU1	"Interacting with the headset was frustrating at some moments"	0	3	4	7	0
PEU2	"I made frequent mistakes when playing using the EEG headset"	1	3	4	5	1
PEU3	"To interact using the EEG headset requires a lot of mental effort"	1	8	2	1	2
PEU4	"To interact using the EEG headset requires a lot of physical effort"	3	7	2	1	1
PEU5	"I think it is cumbersome to control the game elements using the EEG headset"	4	4	4	2	0
PEU6	"It was easy to understand how to use the EEG headset to interact with the game"	0	0	5	8	1
PEU7	"The game MindInfinity offered useful information to control the elements of the game (Tutorial, hints, images, etc)"	0	0	2	6	6

Figure 4.8: Table showing the number of answers to the questions asked on both experiments. By the authors.

Figure 4.9 shows the answers of questions asked only in the questionnaire given on the first experiment. Those questions were asked only in the first experiment because the participants played the keyboard version of the game as well, so the questions are comparing the EEG based and keyboard based game versions.

Open questions were also presented to volunteers, producing qualitative data. For the question "if your interaction with the game via the EEG headset was bad or terrible, why do you feel it was so?", one participant mentioned having more training or practicing time before playing the game would have been helpful; one participant mentioned using glasses with the headset

[2]The questionnaire used in Experiment 2 and the responses to it (in Brazilian Portuguese) can be seen completely in the link: `https://docs.google.com/forms/d/e/1FAIpQLSeB3N9-g3-TewiIsrAWrm1pFjEAE-nIqDPXJ4Dc8asHtE9tmw/viewform?usp=pp_url` *Accessed in 26/06/2018*

Ref.	Affirmative	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
	Perceived Usefulness					
PU1	"I prefer to play MindInfinity using the EEG headset(Emotiv Insight) than the keyboard"	0	0	3	1	0
PU3	"The EEG headset made the game easier to play compared to the keyboard version"	1	1	1	1	0
PU4	"I can control more precisely the elements of the game with the EEG headset than the other version of the game with keyboard"	2	0	2	0	0
PU6	"I can control the elements of the game faster with the EEG headset than the other game version with the keyboard"	1	2	1	0	0
PU7	"I can control more elements of the game with the EEG headset than on the other version of the game with the headset"	1	1	1	0	1

Figure 4.9: Table showing the number of answers to the questions asked only on the first experiment. By the authors.

made the fitting of the EEG headset difficult, and another participant mentioned the reason the interaction was bad was probably for not knowing well the functioning of the headset.

For the question "what could be done to improve your experience?", two participants suggested making the instructions on wearing the headset clearer; two participants mentioned more training would be good; and one participant mentioned making a better contrast of colors on the elements of the game.

For the question "leave other comments that you find relevant", one participant suggested it would be nice adding a "boss fight" to the game; another participant mentioned it is hard moving the spaceship in 2 dimensions while the headset is a 3 dimensional object. Finally, one participant mentioned that s/he thinks the game would also be good to have fun in groups because other people can watch the reactions and movements of the one person who is playing the game.

The actual performance in the game was measured as the number of seconds the participant survived in the game, and the results can be seen on Figure 4.10 for the first experiment. The Figure compares the total survival time in the keyboard version and the EEG version of the game for each volunteer. Figure 4.11 shows the volunteers performance in the second experiment, when the participants only played the EEG version of the game.

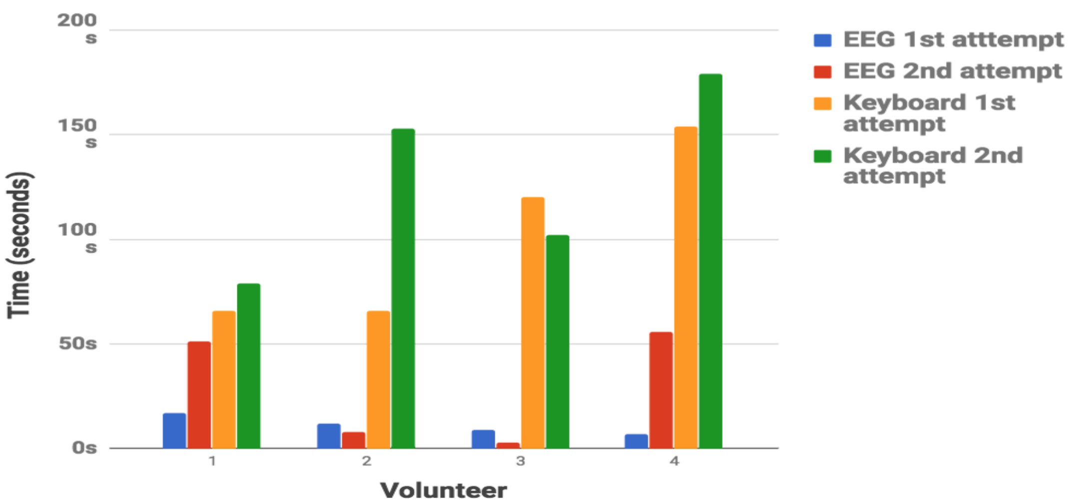

Figure 4.10: Surviving times in the EEG and keyboard versions of the game in the first experiment. By the authors.

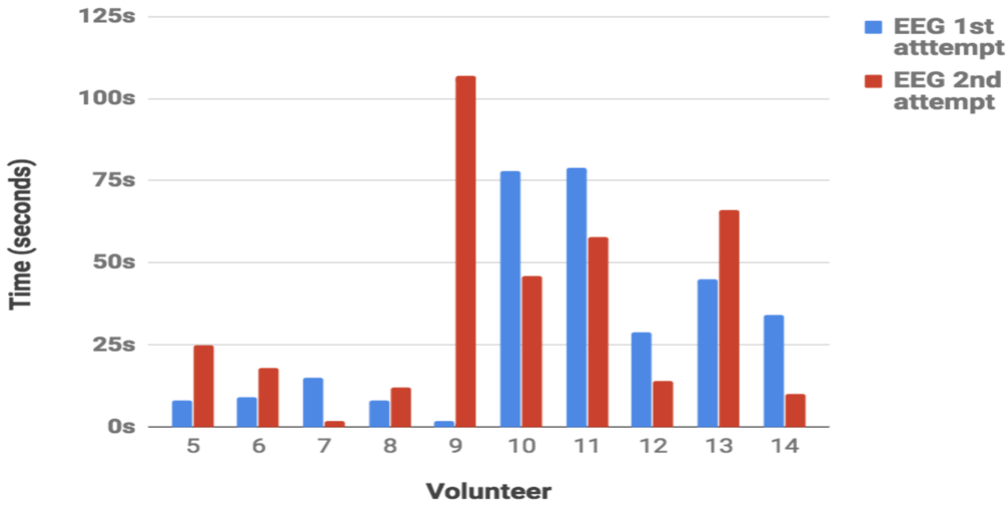

Figure 4.11: Surviving times in the EEG version of the game in the second experiment. By the authors.

It is important to note that, although all participants were instructed to perform the facial expression “frown” so that the spaceship would shoot a triple shot, the EEG headset correctly detected “frown” only for 3 out of the 14 participants: volunteers number 1, 9 and 12. Without the ability to use frown, it is harder to survive for longer in the game since the spaceship shoots less shots, therefore this fact could have influenced the participants’ survival time.

Chapter 5

Discussion

Analyzing the results from the experiments, it is possible to answer the 4 questions posed about the interaction with the Emotiv Insight.

Q1: From the perspective of users, what were the biggest limitations/difficulties on the use of the Emotiv Insight?

Regarding the physical use of the headset, a participant mentioned how difficult it was to wear glasses while using the headset. When conducting the experiments, the researcher found out another problem: people with long hair have more trouble wearing the headset and often needed help to do so. Long hair can also make it harder for the electrodes to detect electric activity in case a person leaves the electrode on top of hair.

Considering the use of the headset as means to interact with the game, six participants agreed to the statement "I made frequent mistakes when playing using the EEG headset." In the first experiment, most participants (3 out of 4) disagreed to the statement "I can control the elements of the game faster with the EEG headset than the game version with the keyboard." Mindinfinity requires a person to be able to react faster with time because hazards in the game keep coming in a faster speed. Therefore, comparing the answers of those two statements, it is possible to link the "mistakes" being caused by a lesser capability to control the EEG version of the game in a fast way (which often ends up making the player reach the *GameOver*).

Looking at Figure 4.10 it is noticeable how playing the same game with the keyboard was much more efficient when it comes to surviving longer in the game. Some of this difference in efficiency was expected since no participant had used an EEG headset before. Furthermore, being able to shoot a triple shot instead of only 1 helps surviving in the game longer and only the participant number 1 in the first experiment was able to do it correctly with the EEG headset. However, everybody was able to shoot the triple shot in the keyboard version. Naturally, results could be different if tests were made with most of the volunteers having hand motor impairments, since using the keyboard would not be possible in many of those cases. However, the participant that reported having RSI in the hands (volunteer number 2) had mostly negative answers toward the EEG version of the game, for example disagreed to the statements PU4 and PU6.

Three people also mentioned having more training time before playing the game would have been helpful. This is, nevertheless, not only the EEG headset's fault, but mostly the game's fault. Maybe, allowing people to repeat the game's tutorial as many times as needed before playing the game with the EEG headset would have been more helpful to them. However, for the experiments, the intention was to analyze the first contact of participants with the game and the EEG device, as their lack of previous experience with both the game and the device can reveal immediate impressions and difficulties. Moreover, for a fair comparison between the EEG version and the keyboard version of the game, participants in the first experiment were allowed doing the tutorial part of the game only once for both the keyboard and EEG versions of the game before playing the actual game.

From the programmer's point of view (the authors), it was really simple to create a program that communicates with the Emotiv Insight. The Cortex API's manual was well written and simple to follow. However, as the information regarding JSON and Websockets is not on the API's manual, the biggest challenge was learning how to use websockets, wrapping and unwrapping some of the JSON messages because they depend on the programming language and the environment where the program is being written.

Q2: How satisfied were users with this form of interaction?

Regarding satisfaction, most participants agreed to the statement "I believe the usage of the EEG headset made the game more fun" and the statement "I believe the usage of the EEG headset made the game more interesting." Besides, most participants (13 out of 14) agreed to the sentence "I adored using the EEG headset to control the application." From those statements and the answer given to the question Q1 above, it is possible to conclude that although using the EEG headset did not make the game necessarily easier to play (players survived significantly less time in the EEG version on the first experiment), it surely made the game more fun to play. This result also agrees with the results shown on the other two studies cited before - the modified World of Warcraft game to use with EEG and the heritage game controlled by EEG ([van de Laar et al., 2013] and [Vourvopoulos et al., 2012] respectively). It is interesting to note that, even though MindInfinity, a concept-simple Space Shooter game, and World of Warcraft have a very different complexity and sizes, adding EEG-controlled mechanisms to these games resulted in similar effects according to the players' point of view: they were not easier to play, but were more fun and interesting.

One interesting note: participants who answered "agree" or "strongly agree" to the questions about the mental and physical effort were participant numbers 2, 3 and 9. Participants 2 and 3 performed poorly regarding the survival time on the EEG version of the game. This could have influenced their negative answers. However, participant 9 was the one who performed worst in the first attempt and best in the second attempt of the EEG-based game. The first attempt could have had an influence on his/her answers, since most participants with average time of survival disagreed or strongly disagreed to the statements PEU3 and PEU4. Also, participant 9 did not know s/he was the one who performed the best among all the participants on his/her second attempt, as the participants were not told to compete nor induced to compete against each other.

Q3: What can be done in the system to help the understanding and usage of the device?

Three participants mentioned having more training time to use the EEG or a longer tutorial would have helped their performance in the game. That is natural, since it was the first time all the participants were controlling movements in a game via their head's movements. In the same way children and adults learn how to move a mouse or type with a keyboard, it is natural to consider that people should be given the necessary tutorial exercises and time to practice their motor skills with the gyroscope of an EEG headset until they feel comfortable to progress.

Another problematic moment was wearing the headset. Participants were left to figure out how to put on the headset only with the information given by the application. However, the instructions on how to wear the headset were not clear to some participants, and the researcher noticed their confusion regarding the side and exact position the electrodes should be placed on the head. A 3D image that could be rotated would have been a better solution to teaching the participant how to wear the headset.

Q4: What was the learning curve of the EEG headset's usage to perform the tasks in the system?

Before answering this question, I point out that the participants played exploring the game interface and elements, in other words, they were not instigated to compete with each other. This factor can influence the resulting survival times in the game.

Figure 5.1 shows how much time each participant survived in their first and second attempts of playing the game with the EEG headset. It is possible to see that in most cases the performance of the participants increased in the second attempt, although this was not true for every participant. One possible reason is the random aspect of the game, since the horizontal positions that the meteors spawn on the top of the screen are randomized and the player can get an unlucky combination of spawns.

Another reason that some participants might have survived less in the second attempt could be that, since the training time with the EEG headset was not sufficient for some people, playing a first attempt might have not been sufficient as well for improving the performance in a second attempt. Also, the fact that players were attempting the frown facial expression while playing the game might have influenced on their concentration at moving the spaceship. As a note, the participants that mentioned having more training time would be helpful were volunteers numbers: 2, 4 and 7, who also did not survive for long on the first or on the second attempt compared to the other volunteers.

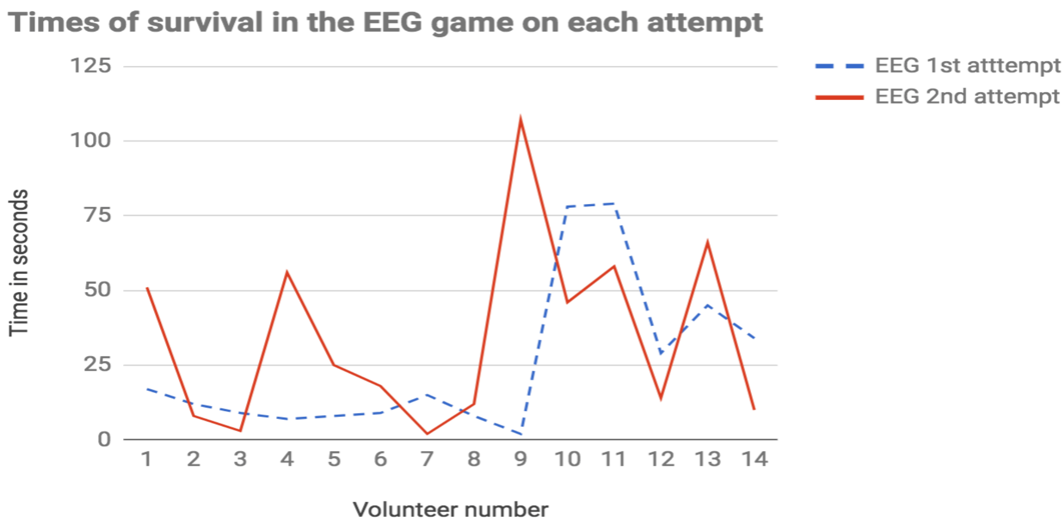

Figure 5.1: Times of survival in the EEG version of the game on each attempt. By the authors.

These reckonings can not be applied to the performance of the participants playing the keyboard version of the game. For 3 out of 4 participants who played the keyboard version, the time of survival in the game increased on the second attempt (see Figure 4.10). The only participant who performed worse in the second attempt of the keyboard version did not perform significantly worse, probably due to the influence of the random aspect of the game.

Finally, in the EEG version of the game, the average survival time of the participants in the first attempt was around 25 seconds, and in the second attempt it was 34 seconds. It is possible to conclude there was an overall increase of survival time of participants in the second attempt of playing the game with the EEG headset.

Chapter 6

Extra: How to 'EEG' Tutorial

In this chapter my goal is to explain the Cortex API's basic workflow and to present an easy to follow example of how to send and receive data from the Emotiv Insight EEG headset. For the send/receive data's example, I will be using MonoDevelop for Unity and the programming language C#. I will also use the Cortex API[1]. Now, let's get started.

6.1 Cortex API's Basic Workflow

When making an account at the Emotiv's website, you can choose from different licensing plans. Here I will describe the workflow on a Basic Plan. If you wish to read raw EEG data or get high resolution performance metrics you need a different license[2].

First of all, you need to call the authorize method. By calling this method you get an "auth" token that will be used on the other method calls. On a basic license you do not need to add any parameters to call the "authorize" method. An example of calling the authorize method is shown on Section 6.1. A session becomes automatically "closed" after 1 min if the headset is disconnected or turned off.

The main concept to understand about the Cortex API is the concept of "session". In order to get information from the headset, first a session needs to be opened. While the session is opened the program can keep receiving data continuously from the headset. One program can only create one session with each headset at a time.

After the session was created, the next step is to subscribe to the data streams you want to receive data from. According to the Cortex API's manual, under the Basic Plan it is possible to subscribe to one of the data streams shown on Table 6.1. After subscribing you will receive the data coming from the data streams chosen until you decide to unsubscribe.

Now you have learned how to get an "auth" token, start a session and subscribe to a data stream. But how about training the headset to recognize an action? In order to train a facial expression or a mental state, you will need to follow the same first steps as before: send "authorize" method and create a session with the headset.

Now you need to subscribe to the "sys" data stream. The "sys" stream shows important information about the status of the training. After that, you need to send the "training" method with an action parameter (for example "neutral") and a status of "start". From the "sys" stream you will receive a message saying the training started and after some seconds you will receive a message saying the training succeeded or failed.

[1] You can see the documentation of the API for more information on the link: `https://emotiv.github.io/cortex-docs/#introduction`

[2] To learn more about the licenses available open the link: `https://www.emotiv.com/developer/`

Table 6.1: The possible data streams to subscribe on a Basic license

mot	Motion data from the accelerometer/gyroscope
com	Mental Command Event
fac	Facial Expression Event
met	Performance Metrics data
dev	Device data include battery level , signal strength, and signal quality all of channel headset
pow	Band Power data
sys	System event (for set up training)

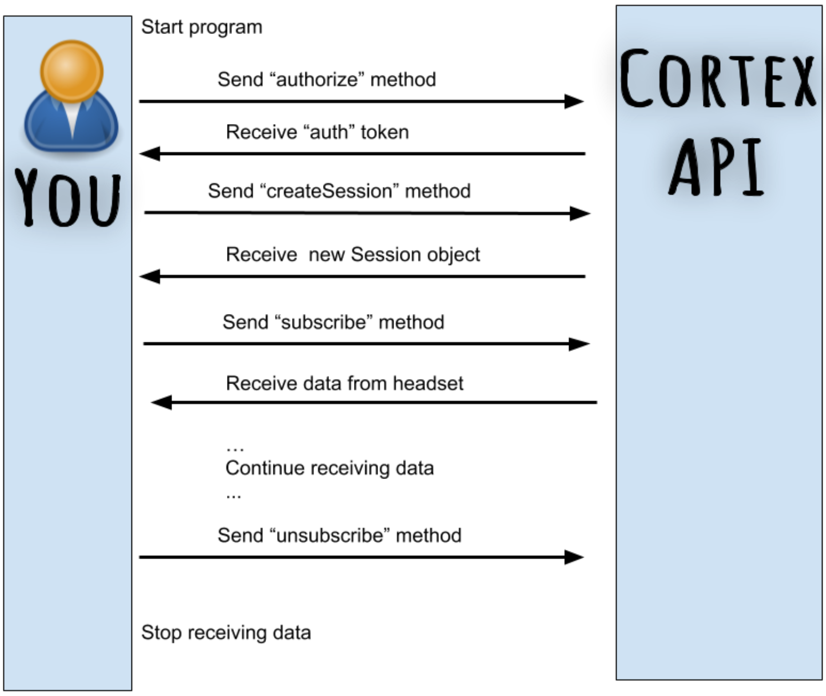

Figure 6.1: Basic workflow of communication. By the authors.

If the training failed all that you need to do is send the "training" again just like before. If the training succeeded you can accept it by sending the "training" method again but now with the status "accept". Finally you will receive another message from the "sys" stream saying the the training is now complete. To stop listening the messages from the "sys" data stream all you need to do is send an "unsubscribe" method to the "sys" data stream.

The infographic shown on Figure 6.1 represents the basic workflow to read data from the headset. The Figure 6.2 represents the workflow of training the headset to recognize a certain person's mental or facial action.

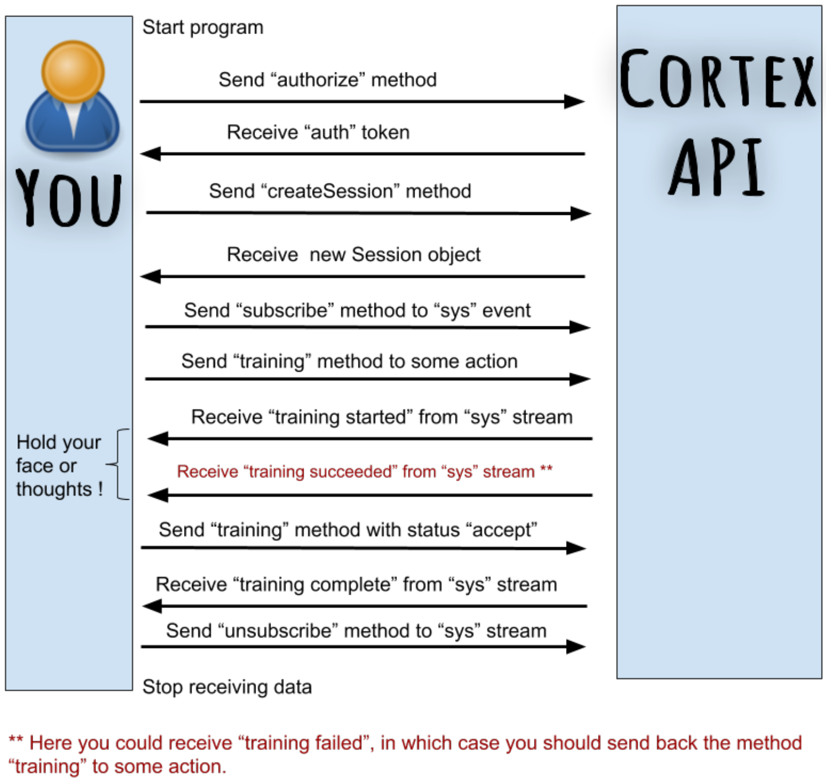

Figure 6.2: Training workflow of communication. By the authors.

6.2 Sending and Receiving Data

6.2.1 WebSocket Creation

First, create a new script called “ExampleClass”. The Cortex API (which will work as a server in this example) communicates via WebSockets. We will need to use a library called “WebSocketSharp” to create a WebSocket. See the code for that below:

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using WebSocketSharp;

public class ExampleClass : MonoBehaviour {

      // Use this for initialization
      void Start () {
         /*Cortex listens on port 54321, therefore we will be
         using the URL below to connect to it:*/
         string URL = "wss://emotivcortex.com:54321";

         /*the command below creates a new WebSocket which
         is saved on the variable "ws"*/
         var ws = new WebSocket (URL);
      }
}
```

6.2.2 Defining WebSocket Actions and Connecting

Before connecting the WebSocket, we need to specify what will be its actions upon opening, error and on receiving a message. I will use the library “System” in order to create an EventHandler, therefore add “using System;” to the start of the code.

```
...
using System;
   ...
   void Start () {
      ...
      /*Here, "treatMessage" is the name of a method to be called
      when the WebSocket receives a message, it will be defined later*/
      ws.OnMessage += new EventHandler<MessageEventArgs> (treatMessage);

      ws.OnOpen += (sender, e) => {
            Debug.Log   ("Opened Socket");
      };

      ws.OnError += (sender, e) => {
            Debug.Log("Error on the socket:"+ e.Message);
      };
      //The command below will connect the WebSocket
      ws.Connect ();
   }
```

6.2.3 Sending an Authorization Request

All the messages sent via WebSocket to the Cortex API must be in JSON-RPC format. The first message I will be sending here is a call to the *authorize method*. This method will authenticate a user and return a token. The token is necessary to call many other methods, so it is important to keep it saved. If you want to know more about the parameters of the message being sent here, please look for “authorize” method at the Cortex API.

```
...
   void Start () {
      ...
      //The message is wrapped in a JSON format
      string message = "{\"jsonrpc\": \"2.0\",\"method\": \"authorize\""+
      ",\"params\": {}, \"id\": 1}";

      //The command below will send the message
      //through the WebSocket
      ws.Send (message);
   }
```

6.2.4 Receiving an Authorization Response

Now that the authorize method has been called, it will generate a response. In order to treat that response and save the “auth token”, I need to specify the method “treatMessage”.

```
...
public class ExampleClass : MonoBehaviour {
   public void treatMessage(object sender, MessageEventArgs e){
      /*The data content of the response is saved into the variable
```

```
      "e.Data" but it will be in a JSON-RPC format, therefore here I use
      the method JsonUntility.FromJson to unwrap the data content.
      The "AuthResultClass" will be explained later.*/

      var generalResult= JsonUtility.FromJson<AuthResultClass>(e.Data);

      /*Next I save the authorization token inside a GameObject that will
      never be destroyed and that holds all the important information.
      This information is defined on another C# program file that
      I call "globalscript".*/

      globalscript.authToken = generalResult.result._auth;
      ws.Close ();
   }

   void Start () {
      ...
   }
}
```

The “AuthResultClass” can be defined in the same file as this code or in another file. This class is needed because the method “JsonUtility.FromJson” needs to know which type of object will it save the data at and in order for it to unwrap the data correctly the object’s class has to mirror perfectly the data coming as response. Looking at the Cortex API’s Manual I can see an example response from the method call “authorize”:

```
{
   "jsonrpc": "2.0",
   "id":1,
   "result": {
     "_auth": "..."
   }
}
```

Looking at the format of the response, it is possible to create a class that mirrors it. This is the class that in the code I called “AuthResultClass”. See its definition below:

```
/*the "[Serializable]" term is used so that the
"JsonUtility.FromJson" method knows
the object can be converted to and from other formats*/

[Serializable]
public class AuthResultClass{
      public int id;
      public string jsonrpc;
      public AuthClass result;
}

[Serializable]
public class AuthClass{
      public string _auth;
}
```

Now you have learned how to send, receive and unpack the received message. By reading the API’s manual you will learn how to send many other method calls to get different type of data from the headset.

As for some methods implemented in the EEG version of the MindInfinity Game, another example of receiving data and using it on a game element is the “3 shots” done by the spaceship when the facial expression “frown” is detected by the EEG headset. The part of the code for receiving the frown data is in a script called “Player.cs” attached to the player Game Object[3]. The relevant parts of code to activating the 3 shots action can be seen below:

```
void Start(){

//create socket to communicate
      string URL = "wss://emotivcortex.com:54321";
      ws = new WebSocket (URL);

      ws.OnMessage += new EventHandler<MessageEventArgs> (treatMessage);

      //send message to connect to accelerometer and facial streams of data
      ws.Send ("{\"jsonrpc\": \"2.0\",\"method\": \"subscribe\",
      \"params\": {" +"\"_auth\": \""+globalscripts.authToken+"\",
      \"streams\": [\"mot\", \"fac\", \"met\"]},\"id\": 2}");
}

public void treatMessage(object s, MessageEventArgs e){
      var generalResult= JsonUtility.FromJson<ResultClass>(e.Data);

      /* some code... */

      //test if message was facial information
      if (e.Data.IndexOf ("\"jsonrpc\":\"2.0\"") == -1 &&
      e.Data.IndexOf ("\"fac\"") != -1) {
            //test if the facial information is frown
            if (e.Data.IndexOf ("\"frown\"") != -1) {
            UnityMainThreadDispatcher.Instance ().Enqueue
            (GetFrownValue (e.Data));

               /* tests if the value (between 0 and 1) indicating how strong
               the EEG headset believes there was a frown expression
               is greater than 0.5*/

               /*Also tests if the last shot time, in order for the
               spaceship not to shoot too many times*/

               if (frownValue > 0.5f && Time.time > nextFire) {

                     nextFire = Time.time + fireRate;

                     //call the method to shoot 3 shots
                     UnityMainThreadDispatcher.Instance ().Enqueue
                     (Shoot3 ());

               }
            }
      }

      /* some code ...*/
}
```

[3]The whole Unity project for the EEG version of the MindInfinity game can be seen and downloaded on GitHub: `https://github.com/lumizila/MindInfinity-EEG`

Chapter 7

Conclusions and Future Work

In this chapter, we intend to point out the overall conclusion over the data gathered with the systematic mapping, the game development and the experiments. Later, a small description of what a future work would be like is given.

First of all, the systematic mapping showed the wide variety of studies already done over the years. With many of them focusing on improving the quality of life of people with disabilities or conditions with prosthesis, exoskeletons, communication devices, adapting browsers and devices for people with motor disabilities, among others. Other studies focused on the general public, to allow self assessment such as the personal attention level when driving or working. Other studies focused on gaming innovations and a few investigated the use of EEG technology for artwork. Although a lot of the EEG-based applications studied were done in USA universities (43 out of 214), there is a fair distribution of such studies over the world, showing the wide popularity of BCI. The growing interest on it over the years is promising, and hopefully we will start seeing a wider usage of EEG-based applications by the general public outside a hospital environment in the near future.

Many EEG headset brands nowadays provide an API which attracts more developers because of the ease of programming for such devices. This was also the case with the headset chosen to used in this research, the Emotiv Insight. The API and the API's manual made it fairly easy for the researcher to develop the game application, considering this was the first time the researcher programmed for an EEG headset. During the tests with the volunteers, the Bluetooth communication and data reached the computer on real time which allowed for a good control of the spaceship's 3 shoots (for those volunteers where the "frown" action actually worked). Indeed, the EEG (and EMG) "frown" data accuracy was not good for most of the volunteers, which probably influenced in their performance and overall satisfaction with the game. The reading of the brain's electric signals can be influenced by many factors, such as poor electrode-scalp contact, dryness of electrodes, poor headset positioning on the head or even low hardware quality.

Four volunteers tested both the EEG headset controlled version of the MindInfinity game and the keyboard version of the same game, while ten tested only the EEG headset controlled version of the game. After the tests with the 14 volunteers, many aspects of the users' EEG headset acceptance and game performance were analyzed.

Overall, the participants showed satisfaction with the EEG headset to control the game, most of them thought that the EEG headset made the game more interesting and fun. However, most participants reported dissatisfaction when it came to effectiveness and speed to control the game elements via the Emotiv Insight. On the one hand, results show that gaming applications controlled via EEG device have a great potential to add fun to games. On the other hand, results gave a hint that using a device such as the Emotiv Insight would not be good for competitive games where the goal of the game is winning a competition, because it requires more training time and even with training it might not be efficient to rapidly control the elements of such a game.

7.1 Future Work

One possible next step to this exploratory research is to develop another game where the spaceship is only controlled by EEG data (excluding EMG data and gyroscope data) and investigate how long would it take for someone to learn how to control their thoughts to play the game and how efficient this controlling method would be. Another possible extension could involve tests with physically disabled people to analyze to what extent such a gaming system can be used by them and what are users' impression about it.

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