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Development of a neurofeedback-based virtual reality environment

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À minha Mãe e ao meu Pai, pela paciência e motivação.

"The [celebrated conception of "free will"] is mythology;
in real life it is only a question of strong and weak will."
-Friedrich Nietzsche

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Abstract

Recent technology has continuously expanded the reaching spectre of psychotherapy. In the latest years, the development of digital environments, coupled with the evolution of sensorial hardware, has demonstrated usefulness and effectiveness in some areas of psychotherapy such as phobia treatment and attention deficit hyperactivity disorder management through neurofeedback training. However, the generality of these equipments is very expensive.

In this project, an audiovisual stimuli virtual reality environment was developed, capable of displaying signals provided by an electroencephalography-based brain-computer interface. This environment has the objective of providing its user with neurofeedback training and being suited for affordable hardware equipments.

Development of the aforementioned environment took place in the Unity3D ® game engine version 5.3.0f4, using C# scripting developed in Microsoft ® Visual Studio 2015 ™. As for the virtual reality display, an Oculus Rift ® development kit 1 was used for testing, together with the Oculus runtime for Windows ®, version 0.8.0.0. The used brain-computer interface was Neurosky's Mindband ™, a research tool with a single electroencephalography channel, mediated through the ThinkGear Connector, version 3.1.8.0.

The creation of this environment as an application directed towards neurofeedback training and compatible with affordable equipments is a contribution towards a reality where virtual reality is more synchronized with our society.

Keywords: Virtual Reality, Brain-Computer Interface, Neurofeedback, Electroencephalography, Psychotherapy, VR, BCI, NFB, EEG

Resumo

Recentemente, a tecnologia tem contribuído progressivamente para o desenvolvimento das metodologias aplicadas em psicoterapia. Nos últimos anos, o desenvolvimento de ambientes virtuais digitais, agregado à evolução de *hardware* sensorial, tem demonstrado particular utilidade e eficácia em algumas das áreas da psicoterapia, como por exemplo no tratamento de fobias e ainda no tratamento de défice de atenção através de treino de *neurofeedback*. No entanto, a generalidade destes equipamentos é muito dispendiosa.

Neste projecto, foi desenvolvido um ambiente audiovisual de realidade virtual, capaz de exibir sinais eletroencefalográficos oriundos duma interface cérebro-computador. Este ambiente tem o objectivo de providenciar ao seu utilizador treino de *neurofeedback* e de ser compatível com equipamentos acessíveis em termos de preço.

Para desenvolver este ambiente, fez-se uso do *game engine* Unity3D ® versão 5.3.0f4, em conjunto com *scripting* em C#, desenvolvido no Microsoft ® Visual Studio 2015™. Quanto à interface de realidade virtual utilizada, foi seleccionado o Oculus Rift ® development kit 1 para testar o programa, em conjunto com o Oculus Runtime for Windows ®, versão 0.8.0.0. Finalmente, a interface cérebro-computador utilizada foi a Mindband ™ da Neurosky ® , uma ferramenta exclusiva a investigação, contendo um único canal EEG, comunicando com o computador através do ThinkGear Connector, versão 3.1.8.0.

A criação deste ambiente com vista a treino de *neurofeedback* e compatibilidade com equipamentos financeiramente acessíveis é um contributo no sentido de que a realidade virtual seja um conceito mais inserido no paradigma da nossa sociedade.

Palavras-chave: Realidade Virtual, Interface cérebro-computador, Neurofeedback, Eletroencefalografia, Psicoterapia, EEG

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Glossary

biofeedback Process of gaining awareness of physiological functions by means of a determined instrument, being able to manipulate them at will.

chromatic aberration The visual effect produced by the refraction of different wavelengths of light through different angles.

dongle Small hardware device that gains additional functionality when connected to another device .

Fourier transform A series of sinusoidal functions resulting from the decomposition of a periodic function.

freeware Proprietary software available for free.

gamification The utilization of typical game elements in the managing of other areas of activity.

hemispatial neglect Neuropsychological condition in which damage to one of the brain's hemispheres generates a deficit in attention and awareness of one side of space.

hyperactivity Exaggerated physical activity.

immersion State in which the mind has the perception of being present in a non-physical world.

object-oriented Defines a programming language which enables a system to be modelled as a set of objects that can be controlled and manipulated in a modular manner.

physiology The branch of biology that analyses the functionality of living organisms and their bodily components.

pixelation Visible presence of small square display elements.

power spectrum Mathematical description of the distribution of power into several frequency components constituting a signal.

psychology The branch of social studies which embraces the study of the mind and behaviour.

psychotherapy The use of psychological methods to improve on a person's mental condition.

shader A computer program used to produce specific levels of color within a graphical component.

Acronyms

3D Three-Dimensional.

ADHD Attention Deficit Hyperactivity Disorder.

BCI Brain-Computer Interface.

Cg C for Graphics.

CV1 Consumer Version 1.

DK1 Development Kit 1.

DK2 Development Kit 2.

ECoG Electrocorticography.

EEG Electroencephalography.

HDMI High-Definition Multimedia Interface.

HDR High Dynamic Range.

HEG Hemoencephalography.

HMD Head Mounted Display.

IBEB *Instituto de Biofísica e Engenharia Biomédica*.

LCD Liquid-Crystal Display.

LDA Linear Discriminant Analysis.

LED Light-Emitting Diode.

MCMI Millon Clinical Multiaxial Inventory.

NASA National Aeronautics and Space Administration.

NFB Neurofeedback.

ns number of signals.

NSD Normalised Slope Descriptor.

nsdr number of samples in each data record.

OLED Organic Light-Emitting Diode.

OS Operating System.

OST Original Soundtrack.

POV Point Of View.

PS4 PlayStation 4.

PTSD Posttraumatic Stress Disorder.

qEEG Quantitative EEG.

RF Radio Frequency.

RGB Red Green Blue.

rtfMRI Real-time Functional Magnetic Resonance Imagining.

SDK Software Development Kit.

SMR Sensory Motor Rhythm.

UI User Interface.

USB Universal Serial Bus.

VCASS Visually Coupled Airborne Systems Simulator.

VIVED Virtual Visual Environment Display.

VPL Visual Programming Languages.

VR Virtual Reality.

VRET Virtual Reality Exposure Therapy.

Chapter 1

Introduction

1.1 Context and Motivation

Technology has been continuously evolving at an exponential rate in the past few decades. With the appearance of computers, science has made unforeseen breakthroughs in many fields, shifting a multitude of paradigms and subsequently creating numerous new technologies, many inconceivable a century ago. We are striving to conquer the seas, the skies, space, life, energy, matter, everything.

This evolution comes as a consequence of the eternal search the human race has pledged itself into, ever seeking to rule triumphant against the forces of nature - We seek to defeat calamity, disease and death, while pursuing comfort, entertainment and life itself. Nature, however, is a tenacious opponent; we have uncovered much, and yet, there is still much more to be uncovered. One of the most intriguing mysteries nature has presented us with, lies ironically within the element which enables us humans to unveil any kind of mystery: The human mind.

Even though we already understand the anatomical and physiological constitution of our brain, the framework of the mind is a far more complex reality to decode. It involves the way we perceive reality, the thoughts we create, the emotions we experience, the reasonings we build, the memories we store and the shady works of our subconscious. Altogether, these elements of the mind synergize in the most incomprehensible of ways, producing the experience of human conscience. Endeavouring to decipher this unsolvable labyrinth we call mind, humankind created long ago the scientific field of psychology.

Through the rise of recent technologies, new approaches on the human mind can be made, allowing for Psychology to develop in ways which were not possible at all in the past. One of such technologies is VR.

Through VR, the creation of an immersion environment becomes facile, enabling a variety of psychological studies and therapies according to the design of the environment. One of such therapies is NFB. However, currently available NFB technology, besides being mostly incompatible with VR, is still very expensive.

1.2 Objectives

The prime objective for this thesis project arose as follows:

- Development of an immersive VR environment which enables the user to be conscious of his own mental state through a visual interpretation of electrophysiological brain signals. This environment will stand out due to the combination of its VR compatibility and the general affordability of its BCI and VR equipment.

In order to reach this final intent, a subset of secondary goals had to be established for the project. These are described below, in chronological order:

- Choice of the hardware and software to interact with;
- Creation of the VR immersion environment;
- Establishment of a connection between the environment and the selected BCI;
- Establishment of a connection between the environment and the selected VR HMD;
- Preliminary testing of the environment's efficacy as an attention NFB tool;

1.3 Dissertation Layout

This dissertation is comprised of six chapters, including the present one, a chapter which contextualizes the reader on the motivations that led to the creation of such a project. The remaining chapters are organized in the following fashion:

- **Chapter 2** presents and describes all of the theory that directly sustains the creation of this thesis;
- **Chapter 3** exposes in detail the existing cutting edge technology which may concern the objective of the project;
- **Chapter 4** explains which materials and methods were chosen for the development of the project, and why they were chosen;
- **Chapter 5** reports on the final product resultant of this thesis, commenting on some of its particularities;
- **Chapter 6** delivers the general conclusions of this project, while presenting some ideas for future work.

Chapter 2

Theoretical Background

2.1 Virtual Reality

Virtual Reality (VR) is a broad term used to refer to multimedia that replicates immersive environments, simulating real life experiences by recreating different kinds of sensory input; these can include taste, smell, touch, sound and sight.

In 1993, author Michael R. Heim described VR as seven distinct concepts in his works: simulation, interaction, artificiality, immersion, telepresence, full-body immersion, and network communication [1]. Throughout history, however, the conception of VR has metamorphosed, becoming essential to delve in history to fully understand the meaning of VR.

The development of the concept of VR can be traced back to the 1950s, when cinematographer Morton Heilig developed the Sensorama™ simulator. The simulator consisted of a color video display with sound, scent, wind and vibration experiences. However, being a film, it did not require user interaction at all [2, 3].

Heilig also developed the Telesphere Mask™, a precursor of the HMD concept. The Telesphere Mask provided sound and blew air currents, just like the Sensorama™ [4].

In 1961, Philco Corporation® engineers developed Headsight™, a HMD enabling closed-circuit remote surveillance through the use of a camera with magnetic tracking of the user's head direction. However, this HMD was only able to provide the user with mechanical film. Computer generated imagery had not been researched yet [5].

One of the first people to present revolutionizing ideas regarding the VR concept was Ivan Sutherland in 1965, who described an ideal immersion environment as "[...] a room within which the computer can control the existence of matter.". He initially called this concept The Ultimate Display [6]. Three years later, he would create what is vastly considered to be the first VR HMD system, "The Sword of Damocles", a system which supported a stereo view of a computer generated environment. This HMD corrected its display according to the user's head position and orientation [7].

In the mid 1970s, the University of Connecticut developed VIDEOPLACE™, a technology capable of combining a person's video-image with a computer generated environment, with no need of a HMD. Instead, a camera and a projection screen made this technology possible [2, 5].

In 1982, Thomas Furness developed the Visually Coupled Airborne Systems Simulator (VCASS) at the US Air Force's Armstrong Medical Research Laboratories. This system consisted of an advanced flight simulator which supplied the pilot with additional flight information through the use of a HMD[2]. Later in that decade, he would be responsible for the direction of the Super Cockpit program, a project aiming to create a more naturally perceptual interface for the pilot, reducing the complexity and number of controls from a regular cockpit. He achieved this through the use of a HMD which, besides supplying flight information like the VCASS, was able to translate gestures, utterances and eye movements into control modalities [8].

In 1985, Michael McGreevy created the Virtual Visual Environment Display (VIVED) at the National Aeronautics and Space Administration (NASA)'s Ames Research Center. This project represented a relatively cheap, small-scale VR immersive simulation that made use of a HMD. This would eventually raise commercial interest in VR systems [9].

In the late 1980s, the company Visual Programming Languages (VPL) Research® released some of the first commercially available VR devices: DataGlove™, a hand gesture input device which recognized finger bending, positioning and orientation, containing feedback tactile vibrators [10] and EyePhone™, a HMD containing twin Liquid-Crystal Display (LCD) screens and stereo sound, as well as compatibility with the DataGlove™ [11]. Jaron Lanier, one of the founders of VPL Research®, was the person to coin the term Virtual Reality, in 1989 [12].

However, approximately at the same time VPL Research® released the EyePhone™, Autodesk Inc.® released its Cyberspace®, a HMD which came with a glove of the same kind that VPL produced, intended as a visualization tool for use with Autocad®[13].

In the beginning of the 1990s, the concept of VR gained enormous popularity. Media like Star Trek, Lawnmower Man and The Matrix divulged the term, earning VR a place in pop culture. Many VR products were developed at the time with commercial designs - mostly for gaming, but also with therapy and training purposes, among others [2].

In beginning of the 2000s, many VR products could already be found in the marketplace. By 2007, Google® launched Street View®, a feature which provided panoramic views of several streets in the world through Google Maps and Google Earth [14].

In 2012, the Oculus® VR company was founded by Palmer Luckey and Brendan Iribe, funded through a Kickstarter® campaign. Their first product, the Rift®, released in the year of the company's foundation, has emerged as the most popular VR HMD in the present. An image of it can be found below in figure 2.1. Meanwhile, in 2014, Facebook® acquired the company [15].

Figure 2.1: The Rift®, a VR HMD developed by Oculus®

To conclude, VR has slightly shifted, along the last century, its meaning and significance; through technological development and cultural trending, it is now defined as, quoting Oculus®, "[...] an immersive medium [which] creates the sensation of being entirely transported into a virtual (or real, but digitally reproduced) three-dimensional world [...]" [16]. It is a commercially available asset, expensive but increasingly popular and, as such, extensive research is being conducted in order to evolve it further; it will keep evolving, and when it finally becomes affordable there is a high chance VR will gain a new dimension and a more dominant role in society.

2.2 Psychology

Psychology is the branch of social sciences responsible for the study of the mind. As such, in addition to trying to decipher the process of thought and the experience of consciousness, psychology tries to assess and treat mental ailments and disorders. In today's fast-paced digital world, our mind has become undeniably formatted by technology and, as a consequence of this transformation, a new area blossomed in psychology - Cyberpsychology.

2.2.1 Cyberpsychology

Cyberpsychology encompasses the study of the interactions between the human mind and computer multimedia, which have become increasingly abundant since the internet became commercialized [17].

Living in the age of information has advantages and disadvantages. Everyone is connected, but because of this cyber-connection, mental disorders surge, such as issues in self-esteem and depression; social networks undermine our mental well-being and videogames instill sleep disorders and cardio-metabolic disturbances through their addiction [18, 19].

To counter these ill effects, psychology is trying to apply computer technology to psychotherapy, for instance conducting online counselling through e-mails, online chats or video conferences. The true effectiveness of this kind of counselling has always been contested, though [20]. On the other hand, VR has proven to be an effective method for conducting specific types of therapy, possibly moreso than conventional therapy methods [21]. The following chapter elaborates on some of these therapies.

2.2.1.1 Types of therapy

Exposure therapy focuses on immersing patients in environments where they feel anxious, in order to build self efficacy so as to confront such situations in real life more successfully. It is a relatively common procedure in psychology [22].

Classical procedures for this kind of therapy include flooding, implosion and systematic desensitization.

Both flooding and implosion involve exposure to anxiety-arousing stimuli for prolonged durations, the difference lying in the method of exposure: While flooding presents the patient with real stimuli, implosion involves only imagination-induced stimuli [23].

Systematic desensitization, on the other side, involves teaching relaxation techniques to the patient and then having him cope with his anxieties by applying these techniques while in anxiety-inducing environments, either real or imagined [24].

Exposure therapy has shown particular effectiveness while treating phobias and Post-traumatic Stress Disorder (PTSD), and since the moment in which VR became able to create semi-realistic environments that the concept of Virtual Reality Exposure Therapy (VRET) appeared. VRET is practical, since, contrarily to traditional flooding, it does not imply arranging for a real environment and, unlike traditional implosion, does not depend on the imagination capabilities of the patient. In recent studies it has shown relatively effective results [25, 26].

Apart from exposure therapy for anxiety-related disorders, VR appears viable and promising in a couple of other psychological conditions such as hemispatial neglect and Attention Deficit Hyperactivity Disorder (ADHD).

When applied to patients with hemispatial neglect, VR seems to provide a more precise and sensitive diagnosis than traditional diagnosis methods, providing therapists with a detailed description of a patient's deficit in Three-Dimensional (3D) space, which might help direct training. It also appears to be more appropriate for monitoring the recovery of patients [27].

As for ADHD, VR environments have been developed in order to produce mental training which antagonizes the disorder [28]. An example of these environments can be found below in figure 2.2. Neurofeedback elements have also been applied to some of these VR environments, with positive results [29].

Figure 2.2: Distractions in a VR environment, created for ADHD diagnosis and therapy. Adapted from [28]

2.3 Electrophysiology

Electrophysiology refers to the branch of physiology that is concerned with the electrical phenomena associated with any kind of bodily activity. For this thesis, we focus on the neuronal monitoring methods existent in electrophysiology.

2.3.1 Electroencephalography

EEG is a medical imaging technique first applied in 1924. By recording the electrical activity present on the scalp, it becomes possible to directly infer on the electrical activity occuring in the brain. This procedure is absolutely non-invasive, and as such it can be repeatedly applied to patients with no kind of risk [30].

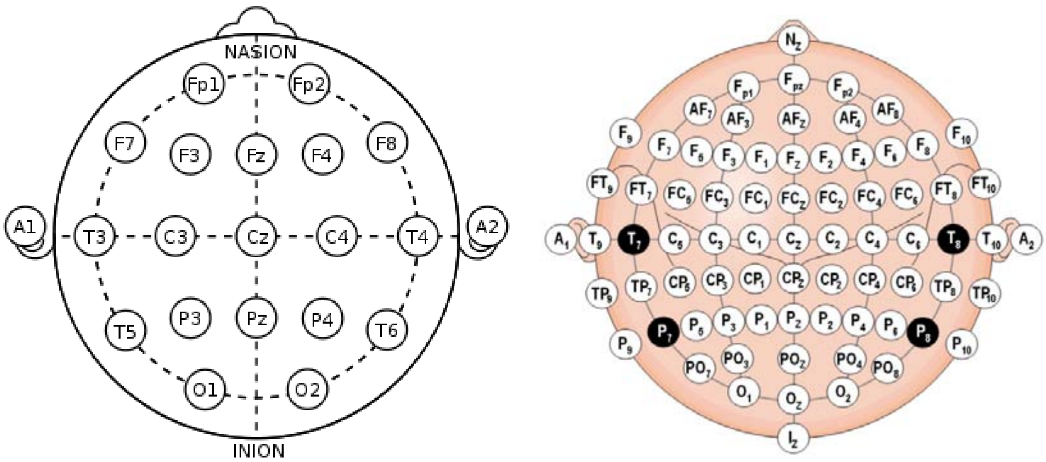
In order to process the information contained in a raw EEG signal, the two steps usually employed can be described as follows [31]:

- Feature extraction - This step aims at selecting the relevant values from the general information contained in a raw EEG signal, thus excluding noise and non-relevant information. All of the extracted features are generally compiled in a vector, known as a feature vector. Examples of these features include power spectrum bands, such as beta and alpha waves;
- Classification - This second step assigns a class, correspondent to a specific mental state, to a set of features extracted from the signal.

Regarding feature extraction, there are 3 main sources of information to be considered when working with BCIs: Spatial information, spectral information and temporal information.

2.3.1.1 Spatial Information

The conductors which contact with the scalp are called electrodes, and its placement has been the subject of thorough study. By selecting specific channels, different areas of the brain can be studied. In figure 2.3 typical configurations of electrodes can be observed.

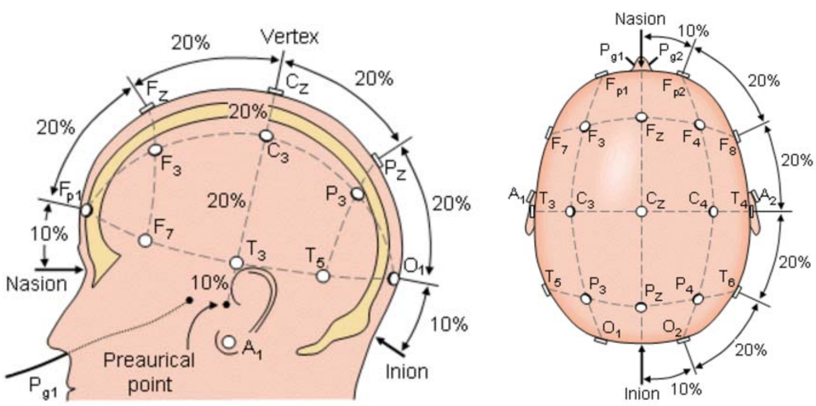


a Location and nomenclature of the 10-20 system

b Location and nomenclature of the 10-10 system

Figure 2.3: The most common systems of electrode placement

As reference points for positioning, the electrodes used are the nasion, placed in the delve at the top of the nose, and the inion, placed in the bone lump at the base of the skull at the back of the head. From these points, the skull perimeters are measured and divided in appropriate percentage intervals. In figure 2.4, the typical distribution of intervals for a 10-20 system can be seen [32].



a Perspective from the left side

b Perspective from above

Figure 2.4: The 10-20 system for electrode placement. Adapted from [32]

The 10-10 system only differs from the 10-20 in the sense that instead of the 20% intervals, it uses 10% intervals.

2.3.1.2 Spectral Information

Typically, raw EEG signals range from 0.5 to 100 µV in amplitude and commonly form sinusoidal wave patterns. By means of a Fourier transform, we can obtain a power spectrum from the raw EEG, allowing to scrutinize the dominance of certain frequencies over time. These frequencies appear in specific regions of the brain and are categorized as follows [30]:

- Beta waves: (13-30 Hz) measured in the parietal and frontal lobes, these waves are regarded as the "normal" brain activity, corresponding to someone who is awake and with his eyes open;
- Alpha waves: (8-13 Hz) measured in the occipital region, they evidence an awake albeit relaxed consciousness;
- Mu waves: (8-12 Hz) measured in the sensorimotor cortex, they show a rest-state of the motor neurons;
- Delta waves: (0.5-4 Hz) measured in the frontal region, these waves are typically associated with a deep sleep state;
- Theta waves: (4-8 Hz) measured in various regions, they may represent a state of lethargic consciousness or light sleep;
- Gamma waves: (> 30 Hz) measured in the somatosensory cortex, they translate a state of active information processing in the cortex.

2.3.1.3 Temporal Information

Temporal features of an EEG signal involve the analysis of EEG signal values at different points in time or in different time windows. To select the optimal points in time for this analysis, several statistical indicators are used; these are known as time domain parameters [31].

One of the most commonly used sets of indicators for EEG processing are the Hjorth parameters; these three parameters are called the Hjorth Activity, the Hjorth Mobility and the Hjorth Complexity. They are Normalised Slope Descriptor (NSD)s which can be described in the following terms [33]:

Activity constitutes the signal's power, which can be translated as the surface of the signal's power spectrum. It is illustrated as the variance of the time function corresponding to the representation of the signal. It can be displayed as follows:

$$Activity = var(y(t))$$

Mobility refers to the mean frequency of the power spectrum. It can be described as such:

$$Mobility = \sqrt{\frac{Activity(\frac{dy(t)}{dt})}{Activity(y(t))}}$$

Complexity alludes to the change in frequency of the signal, by comparing it to a pure sine wave:

$$Complexity = \frac{Mobility(\frac{dy(t)}{dt})}{Mobility(y(t))}$$

2.3.1.4 Classification

In order to translate the extracted features into mental states, either regression or classification algorithms can be used. By far, the most used algorithms in the BCI community are classifiers, which are characterized by their use of training sets (labeled feature vectors, gathered by means of training examples) [31].

These algorithms either model the area covered by the training feature vectors from each class (generative classifiers) or model the boundary between the areas of these vectors (discriminant classifiers). In BCI, the most used classifiers are of the discriminant kind, notably Linear Discriminant Analysis (LDA) classifiers [31].

LDA classifiers make use of hyperplanes to separate the feature vectors representing each different class. Besides having very low computational requirements, their simplicity makes them good at generalizing unseen data, and consequently suitable for BCI systems [31].

2.3.1.5 Medical Applications

Some of the most important current medical applications of EEG include diagnosis of sleep disorders and assistance of disabled people with daily living tasks through the use of BCIs. However, one of the current preponderant problems in medical applications making use of EEG lies in the availability of clinicial EEG databases; for a more effective use of these applications in medicine, the existance of public databases needs expansion [34].

2.3.2 Electrocorticography

Electrocorticography (ECoG) is a medical imaging technique, invented in the early 1950s, similar in almost every aspect to EEG. The exception lies fundamentally at the level of invasiveness: ECoG is performed by placing a net of electrodes on the exposed cortex[35].

Although this technique demonstrates greater precision and sensitivity than EEG, its high level of invasiveness makes it only viable for certain situations, such as surgery for epilepsy [35].

2.4 Brain-Computer Interfaces

A BCI constitutes a communication route between the brain and an external output device of any kind.

The first traces of BCI technology can be found in the year 1924, when German psychiatrist Hans Berger recorded the first human EEG, creating the first device able to identify human brain activity in history. Since then, EEG has always succeeded as the most widely used method in BCI [36]. However, three different types of BCI can be developed:

- The invasive type, in which the signal reading process is applied to the inside of the grey matter of the brain;
- The partially invasive type, in which the signal reading occurs inside the skull but outside of the brain's grey matter;
- The non invasive type, in which the signal reading occurs outside of the skull, making it the safest and the most useful [36].

In the 1950s, the first wet-brain implants took place when Jose Delgado implanted electrodes into the brains of animals, stimulating them via a radio receiver lodged inside the skull [36].

Two decades later, substantial BCI research was initiated, along with the development of technology like the bionic ear and vision systems for the blind. Also in the 1970s, Jacques Vidal, developer of the scalp-recorded visual evoked potential, coined the term Brain-Computer Interface [36, 37].

During the year 1999, science was able to decode the EEG signals originating from a cat's brain [36].

Along the 2000s, many kinds of research in BCI technology were developed. BrainGate™, the first public BCI game was revealed in 2003, brain-controlled robotic arms were created and tested in 2005 and in 2009 images were reconstructed from a brain to a computer for the first time. Also in 2009, wireless BCI was developed by Starlab®, a spanish company [37].

In 2009, Emotiv Systems™ creates the Emotiv EPOC™(illustrated in figure 2.5 a), a 14 sensor EEG system aimed at the gaming community.

In the year 2011, one of the first BCI headsets aiming at the consumer market is created by Neurosky®. Meanwhile, Neurosky® has developed a series of products like the MindBand™ (illustrated in figure 2.5 b) and the MindWave™. Many other companies develop various other kinds of BCIs like BioBolt™, a brain implant that converts thoughts into movement or the MyndPlay Headset™, a mind controlled video and movie platform [36].

a The Emotiv EPOC

b The Neurosky MindBand

Figure 2.5: Examples of BCIs

2.5 Neurofeedback

NFB describes a specific category of biofeedback that makes use of brain activity patterns to teach self-regulation of self brain function. Typically, this brain activity is measured through the use of EEG, while the method of self-regulation varies [38].

In the late 1950s, two medical doctors made the first contact with this mechanism; Dr. Joe Kamiya, at the University of Chicago, discovered that by using a simple reward system, could train people to alter their brain activity, detected through EEG. Dr. Barry Sterman, at University of California, Los Angeles, discovered that he could train cats to control their epileptic seizures [39].

In the late 1960s, NASA started applying NFB training to astronauts, originally suffering from seizures and hallucinations from exposure to lunar lander fuel. Today, this training is still used, although for focus and attention purposes[39].

Along the 1970s, NFB caught attention of religion, being used as a tool of meditation in some circles. At the time, that connection severed the interest of many researchers in the technique, due to the scientific scepticism of anything regarded as spiritual [39].

Through the next two decades, NFB started being applied as treatment to a series of psychological conditions, suffering a rebirth in the scientific community as a therapy tool [39].

In the 2000s, with the change of medical perspectives on the brain, concepts like neuroplasticity gave a total new interest to NFB. Research into the area started gaining interest and investment, and thus many interesting projects were created, including projects that used VR for training mental capabilities like inattention and impulsiveness [40].

In the last years, many different kinds of NFB training were developed. The following chapters particularize on practical applications of the technique [38].

2.5.1 Medical Uses

One of the most clinically proved applications for NFB lies in ADHD treatment. Through the training of attention by means of computer software such as games, both children and adults have demonstrated improvement in their ADHD condition. Generally speaking, the symptoms of impulsivity and inattention show several improvements and hyperactivity shows moderate amelioration [41].

Moreover, NFB shows a lot of promise in several other medical areas, as a replacement for pharmacological medications:

- Real-time Functional Magnetic Resonance Imagining (rtfMRI) training has been used successfully to decrease the magnitude of chronic pain in pain patients [42];
- EEG alpha-theta brainwave treatment has also been successfully applied to chronic alcoholics, using results from a self-rated depression inventory and a Millon Clinical Multiaxial Inventory (MCMI) [43]. Sensory Motor Rhythm (SMR) training has also exhibited success regarding therapy for opiate dependence disorder patients. These cases establish evidence of the effectiveness of NFB in the treatment of addictions [44].
- Quantitative EEG (qEEG) guided treatment has also shown significant efficacy in the improvement of schizophrenia patients [45].

2.5.2 Non-Medical Uses

Other applications for NFB have been successfully researched in diverse areas of art, such as music and dance.

Musical performance, in which practitioners must attain high levels of concentration when playing, has systematically shown improvement through appliance of alpha and theta NFB [46]. Demonstrable benefits have also been proven for acting performance, in consequence of SMR training [47].

In 2015, the My Virtual Dream project took place, submitting 20 participants to artistic video animations and shifting soundscapes driven by their collective neurofeedback, recorded through EEG. Figure 2.6 pictures the project's stage. These kind of initiatives keep furthering our knowledge on the complexity of the creative process [48].

Figure 2.6: The stage in which the My Virtual Dream experience took place

2.6 Game Engines

The video game industry has consecutively pushed software technology onwards across the last 20 years; the need of resort to divergent content for the creation of a game has led to the development of all-embracing 3D platforms which combine physics, audio, animation, scripting and rendering mechanics, now labelled as game engines [49].

These platforms allow for the creation of programmable environments, featuring realistic interaction and thus granting them a place in science and education, also a fruit of the evergrowing awareness of the gamification concept. The use of the Unity3D® game engine can be seen in figure 2.7, while being applied to arachnophobia therapy [50].

Figure 2.7: A Unity3D® generated environment for use in arachnophobia VRET

These engines can be generically represented as a set of modules which handle the input, the output and the physics of game worlds. These do not directly specify the game's behaviour or the game's environment, which have to be defined through the development of game code [51]. Figure 2.8 represents the overall structure of a game engine.

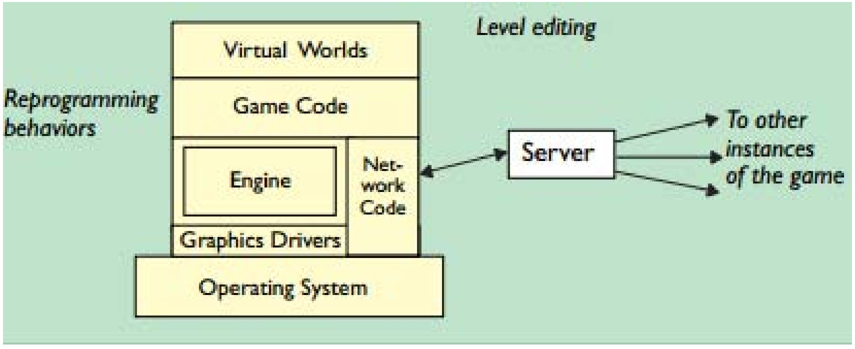


Figure 2.8: Modular game engine structure. Adapted from [51]

As can be observed in figure 2.8, directly under the virtual worlds, which constitute the scenarios with which the players interact, stands the game code, managing the connection between virtual worlds and the inner workings of the game engine; this game code is built in the form of scripts, in a game-specific scripting language [51].

The inner workings of a game engine can be divided into three major components: The network code, which can be described as the main link between an individual game and a server, enabling several users to interact in the same virtual environment; the rendering engine, which essentially manages the player's 3D view; and the graphics drivers, which transform requests from the rendering engine into graphics library requests, communicating directly with the Operating System (OS) [51].

Chapter 3

State of the Art

3.1 Virtual Reality Head-Mounted Displays

The current state-of-the-art VR HMDs competing in the market are the Oculus Rift ®, the Playstation VR ®and the HTC Vive ® [52]. Table 3.1 offers a brief description of each of the main parameters to consider when evaluating a VR HMD.

Parameters	Description
Release Date	Indicates how recent the equipment is.
Display Type	LCD displays use Light-Emitting Diode (LED) backlights to illuminate pixels while Organic Light-Emitting Diode (OLED) displays have pixels emitting their own light.
Screen Resolution	Superior resolutions have more pixels, exhibiting better image detail.
Resolution per eye	The resolution per eye display.
Pixel Layout	Red Green Blue (RGB) contains 3 subpixels per pixel, while PenTile contains only 2 subpixels; although this reduces the image quality, it greatly extends the display's lifetime.
Refresh Rate	Indicates the number of buffer updates per second.
Field of View	The part of the virtual world visible through the display at a given time.
Inertial Tracking	Head tracker which makes use of an imbued accelerometer, gyroscope and magnetometer to track the head's rotation.
Positional Tracking	Head tracker which registers the head's exact position by recognising head movements.
End-to-End Latency	The amount of time between a movement and the reaction showing up on the display.
Wireless	Existence of wireless connectivity to other hardware.
Eye-Tracking	Tracking of the point of gaze of the user.
Integrated Audio	Self-explanatory.
Connectivity	Supported hardware connectors.
Weight	The device's total weight.
Price	The device's current retail price.

Table 3.1: Technical description of the most relevant aspects of VR HMDs

3.1.1 Oculus Rift ®

Oculus VR ® is a virtual reality company, founded in June 2012 and funded in August of the same year through a Kickstarter®campaign. Their first product, The Rift®, had several versions, the initial ones meant for developers, to arouse and excite their willingness of developing VR-related multimedia. The Oculus Rift® has also had extended support for Unity® and Unreal engine® since March 2013 [53]. In figure 3.1, the three versions of The Rift can be observed, while their specifications can be compared in table 3.2.

a Developer Kit 1 (DK1) b Developer Kit 2 (DK2) c Consumer Version (CV1)

Figure 3.1: The three existing versions of The Rift®

Parameters	DK1	DK2	CV1
Release Date	29/03/2013	24/07/2014	28/03/2016
Display Type	LCD	OLED	OLED
Screen Resolution	1280x800	1920x1080	2160x1200
Resolution per eye	640x800	960x1080	1080x1200
Pixel Layout	RGB	PenTile	PenTile
Refresh Rate	60 Hz	Hz	90 Hz
Field of View	90º	100º	110º
Inertial Tracking	Yes	Yes	Yes
Positional Tracking	No	Yes	Yes
End-to-End Latency	50-60 *ms*	20-35 *ms*	25 *ms*
Wireless	No	No	No
Eye-Tracking	No	No	No
Integrated Audio	No	No	Yes
Connectivity	DVI/HDMI + USB	HDMI + USB	HDMI + USB
Weight	380 *g*	440 *g*	470 *g*
Price	300 *$*	350 *$*	600 *$*

Table 3.2: Technical comparison between the 3 released versions of The Rift®[54].

All versions of The Rift® are very light due to the use of high quality plastics and fabrics in their build. The Rift® is supported by the Windows® and iOS® operating systems and even though its original purpose was gaming, The Rift has been successfully used for research in rehabilitation and pain distraction, showing promising results [55].

3.1.2 Playstation VR ®

Playstation VR®, known by codename Project Morpheus during development, is an upcoming VR gaming HMD developed by the Sony Interactive Entertainment® company. This VR product can be seen in figure 3.2.

Figure 3.2: Sony®'s Playstation VR.

In table 3.3, the specifications of the Playstation VR can be observed, seemingly at the level of both the Oculus Rift® and the HTC Vive®. However, Sony® plans on making it an exclusive to the PlayStation 4 (PS4) platform, limiting its usefulness for research [56].

Parameters	**Playstation VR**
Release Date	13/10/2016
Display Type	OLED
Screen Resolution	1920x1080
Resolution per eye	960x1080
Pixel Layout	RGB
Refresh Rate	90-120 Hz
Field of View	100º
Inertial Tracking	Yes
Positional Tracking	Yes
End-to-End Latency	18 *ms*
Wireless	No
Eye-Tracking	No
Integrated Audio	No
Connectivity	HDMI + USB
Weight	610 *g*
Price	400 *$*

Table 3.3: Technical specifications of the to-be released Playstation VR®[56].

3.1.3 HTC Vive ®

The HTC Vive® is a VR HMD developed in a collaboration between HTC®, an electronics company, and Valve Corporation®, a video game company. The HTC Vive can be seen below, in figure 3.3.

Figure 3.3: The HTC Vive, developed by HTC®and Valve Corporation®.

Table 3.4 represents the specifications of the HTC Vive.

Parameters	HTC Vive
Release Date	05/04/2016
Display Type	OLED
Screen Resolution	2160x1200
Resolution per eye	1080x1200
Pixel Layout	PenTile
Refresh Rate	90 Hz
Field of View	110º
Inertial Tracking	Yes
Positional Tracking	Yes
End-to-End Latency	22 *ms*
Wireless	No
Eye-Tracking	No
Integrated Audio	No
Connectivity	HDMI/DisplayPort + USB
Weight	555 *g*
Price	800 *$*

Table 3.4: Technical specifications of the HTC Vive®[57].

The HTC Vive also features a room tracking system, detecting the user's movements in a 1.5x1.5*m* space. This VR HMD is supported by the SteamVR® software for Windows®[58].

3.2 Non-Invasive EEG Brain-Computer Interfaces

Among the many BCIs growing in today's technological market, the brands standing out the most are Neurosky®, EMOTIV®and OpenBCI®. These next chapters elaborate on their products and their particularities, specifying each of the parameters described in table 3.5.

Parameters	Description
Release date	Indicates how recent the equipment is.
Number of channels	Number of existing EEG channels.
Sampling rate	Number of numerical EEG samples registered per second.
Resolution	Number of available bits per channel to store EEG information; higher bit rates allow for the recording of higher spatial frequencies.
Platforms	Supported OSs; "Win" for Windows, "Mac" for Macintosh and "Lin" for Linux.
Wireless	Existence of wireless connectivity to other hardware.
Sensor type	Type of EEG electrode sensors.
Reference type	Type of EEG reference sensors.
Battery type	Self-explanatory.
Battery life	Self-explanatory.
Connectivity	Supported hardware connectors.
Integrated Audio	Self-explanatory.
Format	The device's physical format.
Price	The device's current retail price.

Table 3.5: Technical description of the most relevant aspects of EEG BCIs

3.2.1 Neurosky ®

Neurosky® was founded in 2004, as a manufacturer of BCI technologies. Since then, they have developed many BCI products, both for developers and consumers. Conjointly to its products, Neurosky® has developed a freeware Software Development Kit (SDK), the ThinkGear SDK, which enables independant researchers to develop applications for their devices; this is possible due to the devices transmitting their output through the same serial data protocol, the ThinkGear Communications Protocol [59].

Table 3.6 compares these products' specifications, while figure 3.4 illustrates them.

Parameters	**MindSet®**	**MindBand®**	**Mindwave®**
Release date	March 2007	Info not available	21/03/2011
Number of channels	1	1	1
Sampling rate	128 Hz	128 Hz	512 Hz
Resolution	8 bits	8 bits	12 bits
Platforms	Win/Mac/Android	Win/Mac/Android	Win/Mac/Android
Wireless	Yes	Yes	Yes
Sensor type	Dry	Dry	Dry
Reference type	Earphone Pad	Earclip	Earclip
Battery type	Built-in Li Battery	Built-in Li Battery	1 AAA Battery
Battery life	10 *h*	10 *h*	8 *h*
Connectivity	Bluetooth	Bluetooth	USB RF receiver
Integrated Audio	Yes	No	No
Format	HMD	Headband	HMD
Price	200 *$*	200 *$*	80 *$*

Table 3.6: Technical comparison between 3 of NeuroSky®'s products [59].

a The MindSet®　　b The MindBand®　　c The MindWave®

Figure 3.4: Three of the most featured Neurosky's® BCI products.

All of these products have a particularity, characteristic of Neurosky®: They have only one EEG channel, the Fp1 channel [60].

Through this channel, the ThinkGear™ built-in technology can interpret and transmit some specific types of data: Raw-sampled wave values, poor quality metrics, attention and meditation values and EEG band power values for beta, alpha, delta, theta and gamma brainwaves. The meditation and attention data values are calculated based on algorithms designed by Neurosky® and can be eventually used to raise the user's capabilities by recurring to NFB [61].

3.2.2 EMOTIV ®

Originally branded Emotiv Systems® but later reformed as EMOTIV Inc.®, this company has gained reputation as one of the current lead BCI developers. It has been actively researching BCI technology since 2003 and since then has released 2 major BCI systems: The EPOC/EPOC+® and Insight®. Figure 3.5 demonstrates the products' appearance and table 3.7 elaborates on their technical specifications.

a The EPOC®

b The Insight®

Figure 3.5: EMOTIV®'s current BCI products.

Parameters	EPOC/EPOC+®	Insight®
Release date	21/12/2009	August 2015
Number of channels	14	5
Sampling rate	128 Hz	128 Hz
Resolution	14 bits	14 bits
Platforms	Win/Mac/Lin/Android/iOS	Win/Mac/Lin/Android/iOS
Wireless	Yes	Yes
Sensor type	Saline soaked pads	Semi-dry polymer
Reference type	1 left and 1 right mastoid sensor	2 Left mastoid sensors
Battery type	Built-in Li Battery	Built-in Li Battery
Battery life	12 h	8 h
Connectivity	Bluetooth/USB	Bluetooth/USB
Integrated Audio	No	No
Format	HMD	HMD
Price	800 $	300 $

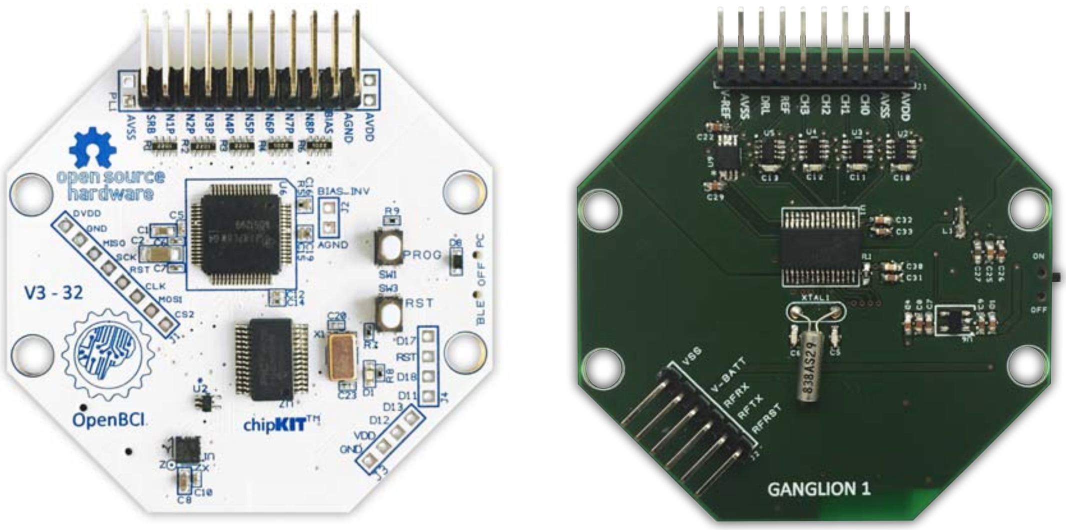
Table 3.7: Technical comparison between the 2 lead products of EMOTIV Inc.®[62, 63, 64].

The EPOC® and the EPOC+® are represented as one single entity since the products have many aspects in common. However, the EPOC+® does feature additional content not present in the EPOC, such as an inertial motion sensor, Bluetooth Smart® connectivity, an alternative 256 Hz per channel sampling rate and also an alternative 16 bit resolution [65].

EMOTIV® features two separate SDK environments, the EMOTIV® SDK Community, a free application, and the EMOTIV® SDK Premium, a paid application. EMOTIV also features a support package for Unity3D® application development, available for 80$ [66, 67].

3.2.3 OpenBCI ®

OpenBCI ® distinguishes itself in the world of BCIs by taking the form of an open-source BCI platform. The project was funded through a Kickstarter campaign in late 2013 and since then has seen thorough expansion in its user database. The platform has several boards available for purchase, and being an open-source platform, its goal is for developers to acquire basic components and develop new software in a public and collaborative form [68]. Figure 3.6 showcases OpenBCI®'s available boards, while table 3.8 describes their specifications - Since these equipments only include the processor board itself, only some of the previously described BCI parameters are displayed.



a The 32bit Board®   b The Ganglion Board®

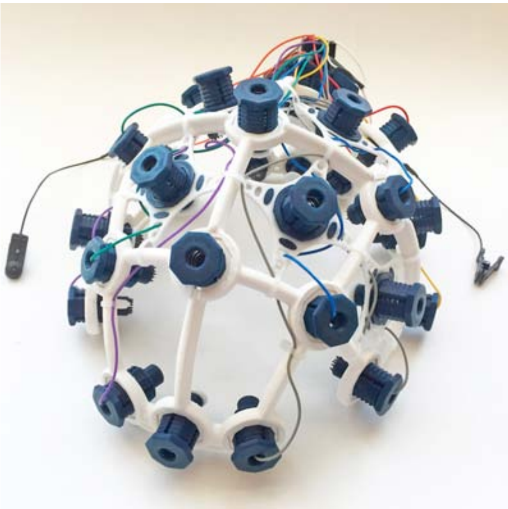
Figure 3.6: OpenBCI®'s available board kits.

Parameters	32bit Board kit	Ganglion Board Kit
Release Date	December 2014	Scheduled December 2016
Number of channels	8	4
Resolution	24 bit	24 bit
Platforms	Win/Mac/Lin	Win/Mac/Lin
Wireless	Yes	Yes
Connectivity	Bluetooth/USB	Bluetooth/USB
Price	500 $	100 $

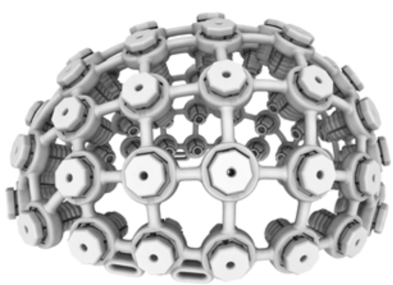
Table 3.8: Technical comparison between the 2 boards developed by OpenBCI®[69, 70].

The superlative advantage of this platform is its flexibility: For a developer, it is the perfect tool since it offers complete customization, software-wise. As for the counterpart, it becomes much harder to develop on such a versatile platform rather than on the straightforward, limited products offered by the standard BCI companies.

OpenBCI has also developed HMDs separately. These HMDs are fully compatible with any of their boards [71]. On figure 3.7, two of OpenBCI®'s HMD products can be observed.



a The Ultracortex Mark III®



b The Ultracortex Mark IV®

Figure 3.7: OpenBCI®'s available board kits.

3.3 3D Game Engines

Among the diverse game engines available nowadays, two of them stand out mainly due to their cross-platform support: Unity3D® and Unreal Engine®.

3.3.1 Unity3D ®

Unity Technologies SF® , the developer of Unity3D®, is a company originally founded during the year 2004. Since then, Unity3D® has become arguably the most popular game engine in industry, spawning renowned game tiles such as Blizzard®'s HearthStone, Ubisoft®'s Assassin's Creed - Identity or even Niantic® 's Pokémon Go [72].

Since their firstly launched products that they have adopted a multi-plan policy, always creating both free and paid versions of their software. Their latest product, Unity3D® 5, was released during March of 2015; figure 3.8 exhibits this workspace's general set-up.

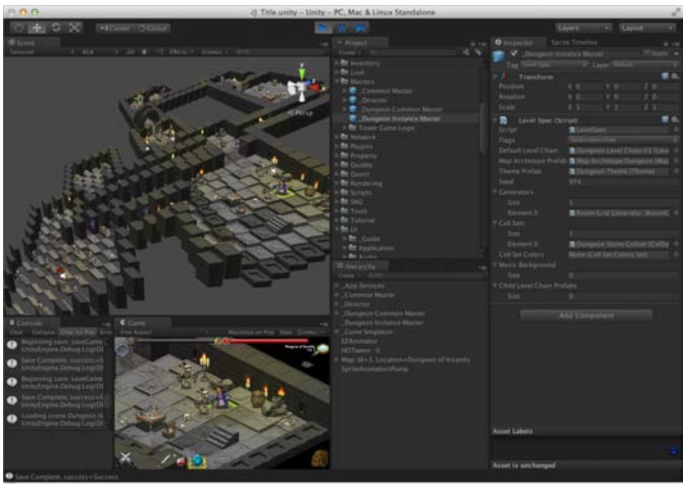


Figure 3.8: A typical user interface in Unity3D® 5.

Some of Unity3D® 5's features include global illumination together with physically-based shaders, High Dynamic Range (HDR) sky-boxes, reflection probes, a new audio mixer and enhanced animator workflows. Platform support includes Windows®, OS X, Unity®Webplayer, Android®, iOS®, BlackBerry®10, WindowsPhone®8, Tizen, WebGL, PlayStation3®, PlayStation4®, PlayStationVita®, WiiU®, New Nintendo3DS®, Xbox 360º®, Xbox One®, Android®TV, Samsung®Smart TV, Oculus®Rift and Gear VR®. Scripting in Unity® can be primarily written in C#, JavaScript ou UnityScript [73].

The various available plans for the current version of Unity® include the Personal plan, a free plan, the Plus plan, available for 35$ per month, the Pro plan, available for 125$ per month, and the Enterprise plan, a plan targeting organizations. Differences between plans include features such as access to asset kits, access to the pro editor UI skin and source code access [74].

3.3.2 Unreal Engine ®

Originally showcased by the Epic Games® game company in 1998, the Unreal Engine®, like Unity®, has been used to create major game titles such as Unreal Tournament, Bioshock and Deus Ex. Since its creation that it has had a core role in gaming industry, only obfuscated by the recent success of Unity®[75].

Unreal Engine®is currently at version 4. Albeit it used to require a monthly subscription fee, the company's current policy is to grant free access to all users and then charge royalties according to the revenue generated by the developed products [76]. Figure 3.9 illustrates the user interface of the Unreal Engine ®4.

Figure 3.9: The interface of Unreal Engine®4.

Its features involve total source code access, a powerful visual effects editor and an advanced shading system. The supported platforms for the engine include Windows®, PlayStation 4®, Xbox One®, Mac OS X®, iOS®, Android®, HTC Vive®, Oculus Rift®, PlayStation VR®, Daydream®, Samsung Gear VR®, Linux®, SteamOS, and HTML5. You can run the Unreal Editor on Windows, OS X and Linux. Scripting in the Unreal Engine® can be primarily done in C++ [76, 77].

3.4 Neurofeedback Technology

State-of-the-art NFB research has already allowed for the development of fully integrated NFB systems. These systems contain both the software and hardware required to perform NFB training and are produced by companies such as NeurOptimal®, Brain-trainer® and BrainMaster®. The cheapest products available from these companies are, respectively, the Personal Trainer Laptop Bundle, the Signature Hemoencephalography (HEG) Package and the Freedom 7D. Table 3.9 specifies the components of each of these products [78, 79, 80].

NeurOptimal®'s Personal Trainer Laptop Bundle	Brain-trainer®'s Signature HEG Package	BrainMaster®'s Freedom 7D
5500 $	**1580 $**	**7000 $**
Windows 10 Laptop System	nIT HEG Headband	Freedom 7d Headset
NeurOptimal® Personal Trainer software	BioExplorer software	BrainAvatar 4.0 software
300 software training sessions	LIFE Game	USB Bluetooth dongle
1 zAmp encoder	x-wiz/Q-wiz Amplifier	Micro USB Cable
1 set of solid silver sensors		Measuring Tape
1 set of earbuds		
2 USB cables		
Conductive paste		

Table 3.9: Description of the equipment included in some of the cheapest NFB training products available in the market [78, 79, 80].

Even though they involve both hardware and software, all of the products are still very expensive. By taking into account that these are the cheapest products available in each of their respective companies, one can establish that the average pricing for NFB integrated systems is, at the moment, high. Additionally, none of these systems include any kind of VR support.

Chapter 4

Materials and Methods

4.1 Materials

4.1.1 Virtual Reality Head Mounted Display

The VR HMD chosen to undertake this project was the Oculus Rift® DK1. The reason for this choice lies in two factors: versatility and availability.

Oculus® features cutting edge technology, and unlike the Playstation VR, it has both Windows® and OS X® support. This factor puts it at the same level of interest than the HTC Vive®. However, the HTC Vive® was not an available asset at the IBEB, thus making the Oculus Rift® the prime choice for the project.

At the IBEB there were two models of the Oculus Rift® available, the DK1 and the Development Kit 2 (DK2); since the DK2 was being used for another project, development for the DK1 took place.

The DK1 included the HMD, coupled with its respective control box, 3 pairs of different lenses, a High-Definition Multimedia Interface (HDMI) cable, an USB cable, the power cord and a DVI/HDMI adapter.

After many experiments with several instances of the Oculus® runtime software for Windows®, version 0.8.0.0 proved to be the most functional in assuring connectivity between the OS and the DK1. Figure 4.1 showcases the runtime, connected with the DK1.

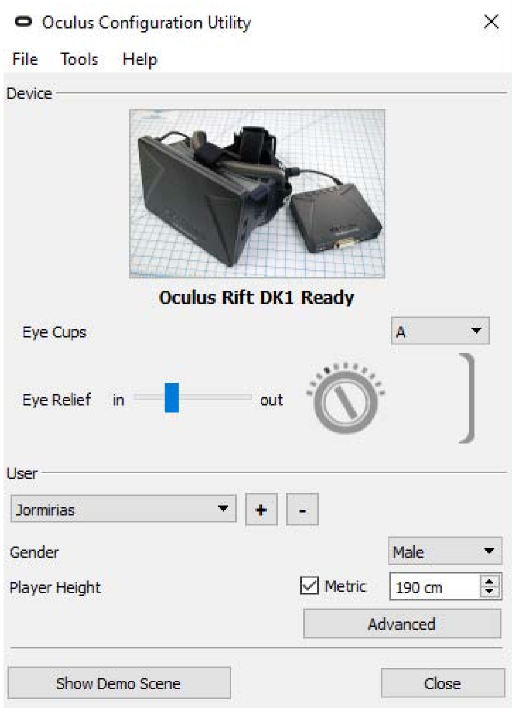


Figure 4.1: Oculus®' runtime software version 0.8.0.0.

4.1.2 Non-Invasive EEG Brain-Computer Interface

Regarding availability, there were several possibilities available at the IBEB: Neurosky®'s Mindband and Mindset plus EMOTIV®'s EPOC and Insight. Since there were so many possible options, the OpenBCI® alternative was prematurely discarded.

After some tests with the EPOC, it became clear that connectivity with the selected game engine could only be achieved through the purchase of a specific connectivity package, supplied only by EMOTIV®. This factor, conjointly with the difficulty of physically fitting the EPOC together with a VR HMD, were very demotivating issues regarding the utilization of the EPOC; and since the Insight was required for another project, EMOTIV®'s BCIs were both put aside.

Between the MindSet and the MindBand, since there were little differences, the preponderant factor was physical compatibility with VR HMDs. This elected Neurosky®'s MindBand as the preferred choice due to its flexible form, allowing for ease of use together with any kind of VR HMD.

The NeuroSky®MindBand kit contained the BCI band, a Bluetooth USB dongle and a USB/mini-USB connection cable.

As for the connector software, ThinkGear Connector version 3.1.8.0 was used, being the most recent version of the software distributed by Neurosky®.

4.1.3 3D Game Engine

The game engine chosen for the development of this thesis was the Unity3D® version 5.3.0f4 for Windows®. This choice ensued from 3 key considerations:

- NeuroSky®'s and Oculus®' well documented cross-platform support for Unity®;
- Previous experience utilizing the C# programming language;
- The considerable size of Unity®'s online community.

Paired with this choice came the consequent need to utilize one of Unity®'s supported script editors, either Visual Studio® or Monodevelop®. Visual Studio 2015® was preferred due to past experience of the author with the editor.

Unity®'s interface is customizable, but its basic set-up is very practical. In figure 4.2 we can analyse this set-up.

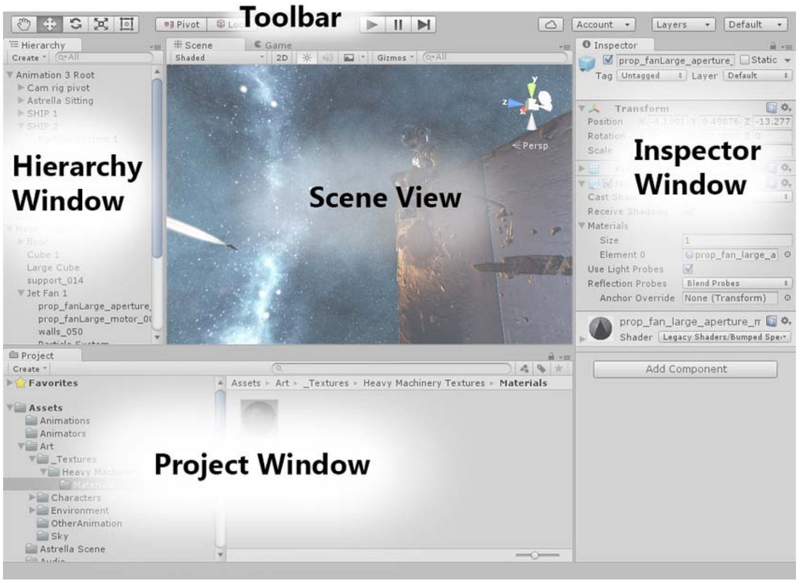


Figure 4.2: Default structure of Unity®'s interface.

A description of the interface's components follows:

- The **project window** displays a library of the available assets to use in the project;
- The **scene view** allows a visual navigation and edition of the scene;
- The **hierarchy window** is a hierarchical text representation of every object in the scene;
- The **inspector window** allows visualization and edition of all of the properties of the currently selected object;
- The **toolbar** provides access to the most essential general working features.

Programming in Unity® involves, very generally speaking, the creation of scenes, the insertion of objects in these scenes, and then the attribution of specific scripts to these objects. This is why scripts in Unity® are object-oriented. In figure 4.3, some of Unity®'s basic classes are illustrated, the arrows representing the level hierarchy between these classes. A class which an arrows point to represents a superior element in the hierarchy.

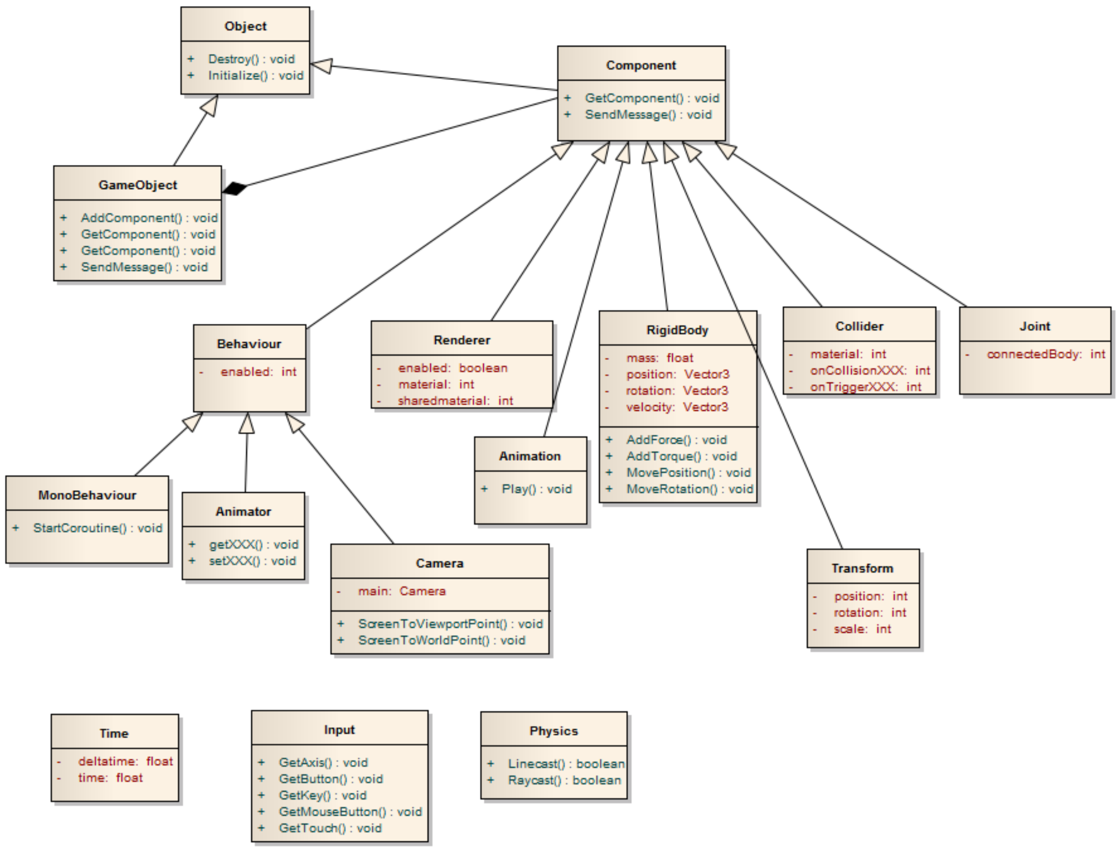


Figure 4.3: Hierarchical representation of Unity®'s classes.

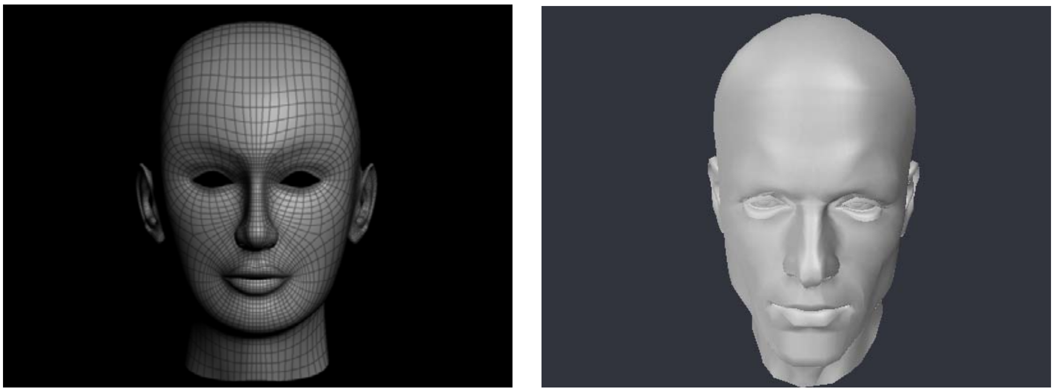
4.2 Methods

4.2.1 Scene Set-up

4.2.1.1 Head Model

To start setting up the scene, a realistic head model was required. This head model would serve as a base for the user to understand the relative positioning of the electrodes, enabling him to easily interpret the EEG data.

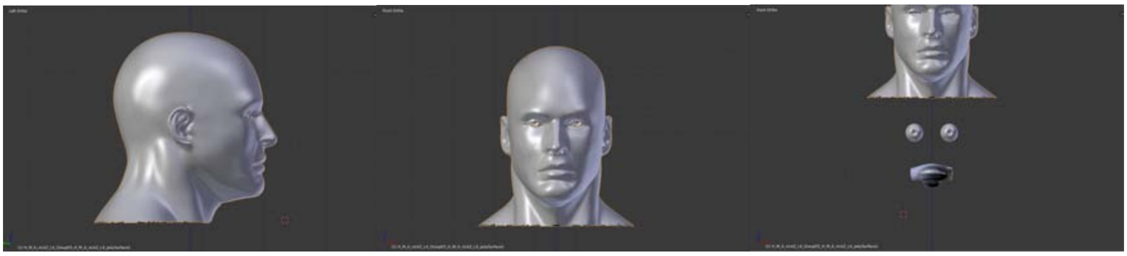
The minimal requirement decided for this head model was for it to have tolerably correct anatomical proportions. By searching the website https://www.cgtrader.com/, a website for online sharing of 3D VR models, many head models were found, some of them represented in figure 4.4.



a Head Model 1 b Head Model 2

Figure 4.4: Head models initially considered for the application

The final selected model was a head model submitted by cgtrader user ionchris, illustrated in figure 4.5.



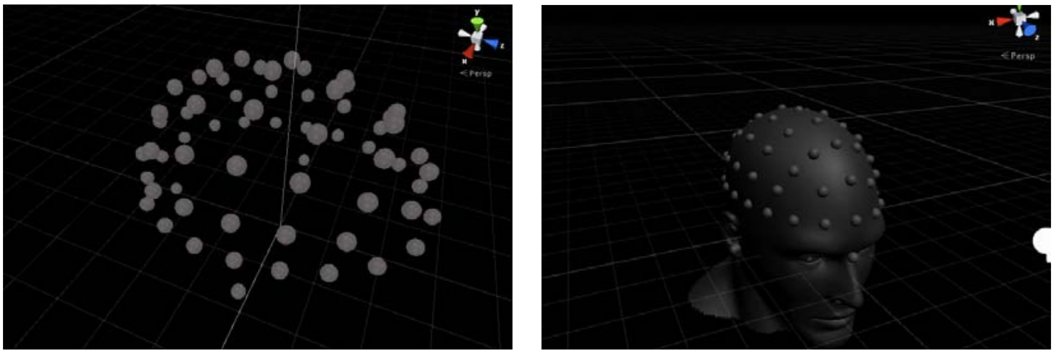
a Side view of the model b Front view of the model c Independent components of the model

Figure 4.5: The head model used for the application

Besides having relatively correct anatomical proportions, the independence of the eye structure relative to the rest of the head would prove useful for later design features. The model was available in .obj format, compatible with Unity®.

4.2.1.2 Electrode positioning

The next step for the setting of the scene was the creation of the electrode objects. 64 sphere objects were created, each representing one of the 64 electrodes present in a 10-10 placement system. Following a manual for the placement of electrodes in a 10-20 system [81], the spherical objects were displaced in the scene according to 10-10 nomenclature, using Unity®'s 3D coordinate system. The result can be seen in figure 4.6. Appendix A contains the spatial coordinates assigned to each electrode object.



a Without the head model. b With the head model.

Figure 4.6: Arrangement of the sphere objects, according to the 10-10 electrode placement system.

4.2.1.3 The base of the head model

At this point, a problem had become evident: The bottom part of the head model was unfinished.

This part of the model would produce a visualization glitch every time the camera was directed towards the base of the model, displaying the model's interior surface as an invisible object.

As a measure to solve this problem, a particle system was created, simulating smoke in order to obstruct the camera view of this part of the model. However, in a later part of the project it became perceptible that this particle system was diminishing the frame rate of the application, demanding too much from the camera rendering system. So, instead of a particle system, a solid object was implemented in order to visually block this part of the model. This object is represented in figure 4.7.

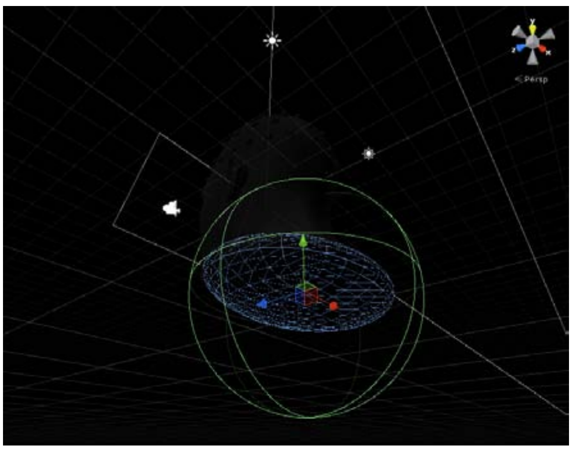


Figure 4.7: The object created as a base for the model.

4.2.1.4 Skybox

Finally, for the scene to be set, a background was required. In game engines there is a specific method of creating backgrounds named skybox. This method applies a cuboid to the camera view of the scene, creating the illusion of distant 3D surroundings.

After a search through Unity®'s asset store, an interesting skybox showed up; skybox volume 2 (Nebula) pack by Hedgehog Team had an excellent rating, was free and presented a spacial setting, which seemed fitting for an application featuring what used to be a science fiction concept. Various skyboxes were available in the pack, and after some experimentation, the DeepSpaceGreen skybox was selected. In figure 4.8, the result can be observed.

Figure 4.8: The DeepSpaceGreen skybox, together with the complete head model.

4.2.2 Visual Effects

4.2.2.1 Lighting

Unity® 's integrated lighting system allows for the creation of light emitting objects. Several settings for these objects were experimented, and since the model was coloured black, 4 different lighting objects had to be created for the model to have its outward linings visibly distinguishable. These objects produced directional lighting from the top of the model, from the bottom and both its sides. The various objects' material specifications also had to be altered in order to reflect light in the intended manner.

4.2.2.2 Camera filters

To produce a smooth experience, several filters were implemented and optimized in the camera object:

- An anti-aliasing filter, to improve the pixelation of the display;
- A bloom filter, which causes light to appear to leak into surrounding objects;
- A vignette filter, which darkens, blurs and introduces chromatic aberration in the edges of the image.

Figure 4.9 illustrates the difference in visual display between the filterless and the applied filter camera object.

a Display without the filters.

b Display with the filters.

Figure 4.9: Comparison between the display with and without filters.

4.2.2.3 Glow

A simple and effective method of transmitting the EEG data to the user seemed to be through the color of the electrode objects. However, to make this visually appealing, solid color did not seem enough; as such, a shader was programmed to simulate glow in the scene objects.

Shader programming in Unity® uses the C for Graphics (Cg) high-level shading language, wrapped in a ShaderLab script. Figure 4.10 exhibits the result of the shader in the electrode and eye objects.

The use of the glow shader in the eyes object was initially merely for aesthetic purposes. However, to increase the environment's dynamism, a script was developed to produce a periodic variation in the eye glow.

Also, as the project advanced, the idea of creating an .edf file reader appeared, and the eyes' color became indicative of the mode the program is currently in: Blue-toned eyes represent the file reading mode and green-toned eyes represent the live BCI mode.

Figure 4.10: The Unity® environment with the shader applied in both the electrode and the eye objects.

4.2.3 Sound Effects

To expand the user's immersive experience, music would be a substantial addition. As such, two tracks were implemented in the program, both being calm, ambient musics: Haggstrom and Subwoofer Lullaby by artist C418, originally utilized in Minecraft®'s Original Soundtrack (OST). A script was also developed to transition between these musics and to mute them.

4.2.4 Scripting

4.2.4.1 Camera Movement

To enable the dislocation of the user's Point Of View (POV), a script which controlled the location of the camera had to be developed. With this objective, an invisible sphere object was created in the approximate center of the head model, and the camera object assigned as its child; this child-parent property forces the camera to maintain its distance toward the parent object, and to accompany its rotation. Following this fashion, a script to control the sphere's rotation was created, since this rotation would be automatically replicated in the camera object.

Horizontal rotation was trivial to implement, since it only required rotation around the y axis, represented in figure 4.11. However, vertical rotation needed the script to be aware of the sphere's current position, relative to the y axis, requiring geometry calculations. An upper and lower limit also had to be established for the vertical rotation, since the rotation would glitch whenever the camera reached the location directly above or under the model.

In order to soothe the POV transition, the script was designed to gradually accelerate the sphere's rotation when the correspondent key is pressed and to gradually decelerate it when the key is unpressed.

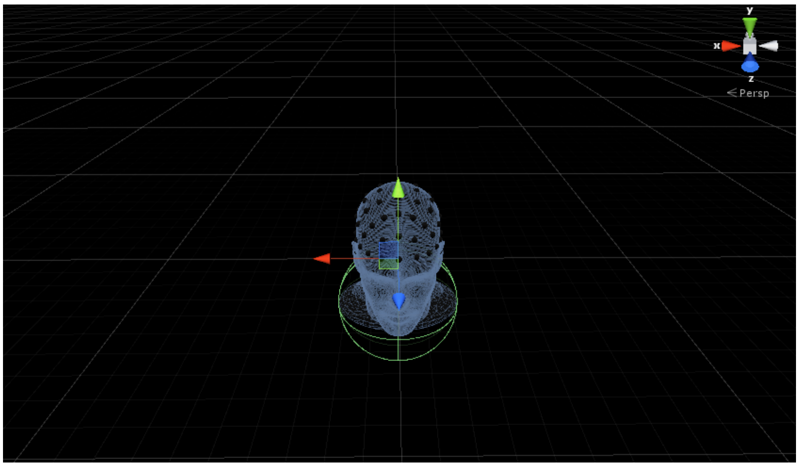


Figure 4.11: Unity®'s scene view, with the y axis represented in green.

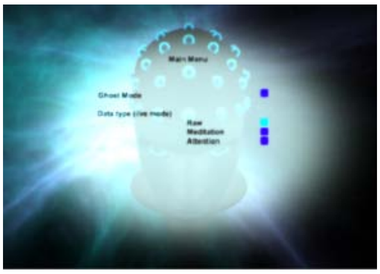
4.2.4.2 User Interfaces

Five UIs were implemented:

- A main menu window;
- A help window;
- A file loader window;
- A "no file name inserted" error message;
- A "non-existent file" inserted error message.

The first three UIs can be activated through a specific key. The main menu window has several interactive toggles, allowing the user to activate or deactivate "ghost mode" and to select the type of represented BCI data. The help window describes the available keyboard commands. The file loader window asks the user for the file name of the .eeg file to load in the program; a script then accesses a specific folder and locates the file requested by the user. Three scenarios can then occur with the latter UI: In case the user did not input any text, the "no file name inserted" error message will appear; in case the name inserted does not correspond to any of the existing files in the folder, the "non-existent file" error message will appear; in case the file exists, its information is processed by the appointed scripts.

In figure 4.12, the five UIs are showcased. In a posterior part of the project, the UIs had to be resized to fit the VR scene.



a The main menu window.

b The help window.

c The file loader window.

d The "no file name inserted" error message.

e The "non-existent file" error message.

Figure 4.12: The several UIs developed for the application.

4.2.4.3 .edf File Loader

Halfway along the thesis, since the Mindband® was not available in the IBEB at the time, an .edf file reader and interpreter was implemented. Overall, .edf files can be divided in three major components:

- The general header record;
- The signal-specific header record;
- The signal-specific data records.

The first 256 bytes of the file constitute the general header and specify the format's version, the patient's identification, recording identification, the start date and start time of the recording, the number of bytes in the header record, the number of data records in the file, the duration of each data record and the number of signals (ns) in each data record.

Next, a header record with 256 bytes for each of the recorded signals follows. That is to say this header record will contain ns × 256 bytes, each component of the record having ns instances, one for each signal. These components are comprised of a label, the transducer type, the physical dimension, the physical minimum and maximum, the digital minimum and maximum, the type of prefiltering and the number of samples in each data record (nsdr).

Finally, several data records are registered. One data record's size varies according to the ns and the nsdr; each data record will contain ns signals, each having nsdr samples, each sample value represented as a 2-byte integer in 2's complement format. These values' units are represented in the physical dimension component of the header record. Figure 4.13 illustrates the detailed format.

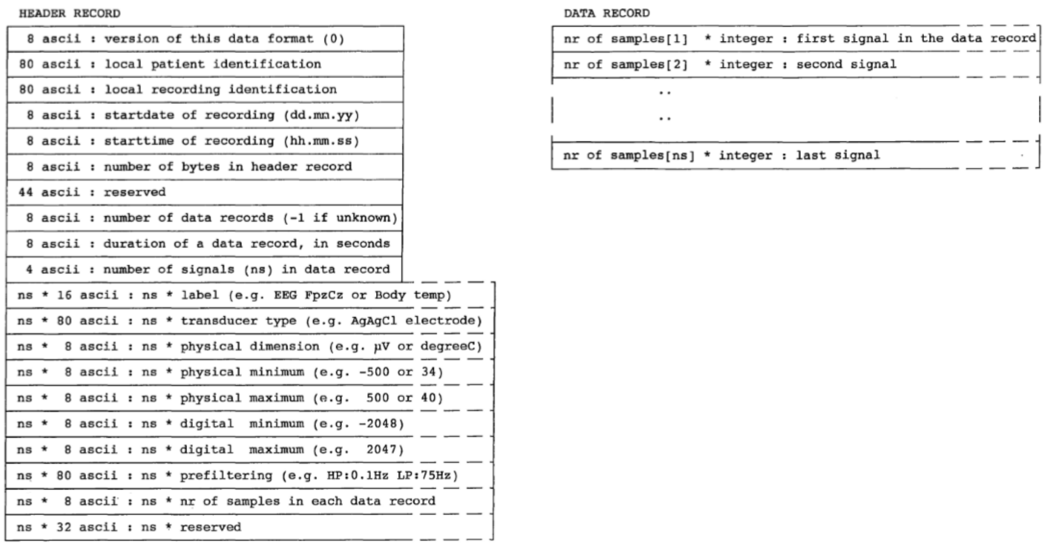


Figure 4.13: Detailed digital format of an .edf file [82].

The process to build a script that reads these files involved 3 steps:

- Creation of 3 classes, one for each of the .edf file components mentioned previously. These classes were labelled "Header", "Header_signal" and "Data_record". A support "Signal" class also had to be created for the "Data_record" class;
- Creation of a "File" class, which contains a "Header" object and several instances of "Header_signal" and "Data_record" objects;
- Creation of the "EDFfetch" script which accesses the file path, processes the information and allocates it in the respective "File" object.

After compiling the .edf information in a "File" object, the object will retain the data until a new file is loaded. The "ElectrodeColor" script will then access the data in the "File" object when the corresponding key is activated. Section 4.2.6.1 elaborates on this script.

4.2.5 Connectivity

4.2.5.1 VR

Connecting the Oculus Rift® to Unity® required only the installation of a Unity® engine integration package, available on the Oculus® website. The selected version of this package was 1.3.0, which presented satisfying interactivity with the Oculus® runtime 0.8.0.0.

To enable the VR display of the environment, the camera object had to be replaced by a camera rig object, a type of object featured in the installed package. To accomplish this, a new scene was created in Unity®, the "Oculus DK1" scene, which differs only from the original scene in the constitution of the camera object and the size of the UI elements. The original scene was thus named "Desktop", since its use is appropriate only for desktop displays.

4.2.5.2 BCI

Neurosky® also features an engine integration package which allows Unity®'s interaction with the ThinkGear Connector. The employed version of this software was 1.1.0.

This package supplies Unity®with various tools, among them a folder with 2 scripts: The "TGCConnectionController" script and the "DisplayData" script. The first script accesses the data transmitted by the Mindband through the ThinkGear Connector, and can be altered to control the rate of accessed data; the latter script is responsible for presenting selected kinds of data (Raw, Meditation and Attention).

4.2.6 Electrode Color

A core element of the application is the "ElectrodeColor" script; according to the current mode the program is in (defined by the "EyeGlow" script), this script can exhibit two different behaviours, described in the sections below. The script was also designed to produce an initial blink effect in the electrode objects, for aesthetic purposes.

4.2.6.1 File Reading Mode

When the application is set in this mode, the "ElectrodeColor" script activates a coroutine which accesses the data currently stored in the "File" object from script "EDFfetch". First of all, this script extracts from the "Header" object the duration of the records and from the "Data_record" object the number of samples in each signal. Afterwards, it runs a cycle which, based on the time passed since it started running (accessible through the "Time" class, available in package UnityEngine), accesses the time-corresponding signal sample. This way, the sample values are accessed in a real-time fashion. As the information is accessed, the corresponding electrode object to each signal will change its color, indicating the current raw value being accessed. The colors chosen to represent the variations were dark blue, light blue, green, yellow and red, each respectfully assigned to a μV range, specified in table 4.1. Figure 4.14 showcases the graphic result of the application of the script.

Colors	**μV**
Dark Blue	< 0
Light Blue	0 - 100
Green	100 - 150
Yellow	150 - 200
Red	> 200

Table 4.1: Description of the raw values indicated by each color.

a Electrode objects representing samples between 100 and 150 μVs.

b Electrode objects representing samples between 0 and 100 μVs.

Figure 4.14: Application running a file while in File Reading Mode.

4.2.6.2 Live BCI Mode

When the live mode is activated, a coroutine is activated in which the electrode objects continuously access the "DisplayData" script, and according to the type of information currently selected in the main menu, display a specific type of activity (Raw, meditation or attention). The raw values use the same color converter table exhibited in the previous section. The other values use specific conversions of their respective units into the color code, showcased in table 4.2. Even though the data is only available from one channel, the Fp1 channel, the color are represented in all electrodes objects for a better visualization experience. Figure 4.15 showcases the graphic result of the application of the script.

Colors	Attention/Meditation level (%)
Dark Blue	0-43
Light Blue	43 - 71
Green	71 - 85
Yellow	85 - 100
Red	> 100

Table 4.2: Description of the values indicated by each color.

Figure 4.15: Application showing Raw EEG while in Live BCI Mode.

4.2.7 Neurofeedback Testing

To confirm the capability of the program to induce NFB training, an experimental procedure was created. Since the MindBand® already contains an incorporated measurement of the Attention and Meditation levels of its user, the formulated procedure was set to target an Attention NFB training.

This procedure was built upon the premise that the act of reading requires Attention and, therefore, that it would provide a good measurement of the Attention level of the test subjects. Previous studies have determined that a higher span of Attention is associated with a slower pace of reading (more specifically, reading speed is inversely related to the results of a Digit Span test, which measures simple immediate span Attention) [83]. The structure of the created procedure is represented in table 4.3.

Control Group	Study Group
Reading of the beginning of book 1, during 2 minutes	Reading of the beginning of book 1, during 2 minutes
The subject was asked to resume what he/she had read	The subject was asked to resume what he/she had read
10 minute break	5 minutes of exposure to the VR environment, and the subject was asked to try to turn the electrode objects red
Reading of the beginning of book 2, during 2 minutes	Reading of the beginning of book 2, during 2 minutes
The subject was asked to resume what he/she had read	The subject was asked to resume what he/she had read

Table 4.3: Experimental procedures applied to the control and study groups.

This procedure was elaborated with the intent of analysing the difference between the number of words read in book 1 and book 2. To determine these, the subjects were asked, after reading the book during two minutes, to which word in the book they had gotten to during their reading. The subjects were informed beforehand that they would only be allowed to read during two minutes.

In between books, the study group was subjected to 5 minutes of NFB training by being asked to, exclusively using their concentration, try to shift the electrode objects' color to red in the developed VR environment.

For a valid comparison with the study group, a control group was created in which, instead of being subjected to the program, the subjects were allowed a 10 minute break between books. This way, by comparing the difference of words read between the subjects of the two groups, one would be able to ascertain if NFB training in Attention took indeed place for the study group (the reading speed is expected to decrease for the study group, after being subjected to the VR environment) [83].

Since the books had to contain a similar kind of writing, two books from the same author, José Saramago, were selected, due to Saramago's particular form of writing. Book 1 was *As Intermitências da Morte* and book 2 was *Caim*. To ensure the readers would minimally pay attention to what they were reading, they were previously warned that they would have to compose a brief resume of both books after they had read each of them. The resumes also served as a means to confirm if the subjects had actually read up until the word they claimed to.

Regarding the choosing of subjects, some conditions were created in set to reduce the number of variables susceptible of affecting the experiment's results; with this purpose, all subjects who contributed had to:

- Contain college-level literacy skills;
- Not have read any of the two books before;
- Possess an age between 18 and 25 years old.

Chapter 5

Results and Discussion

5.1 The Application

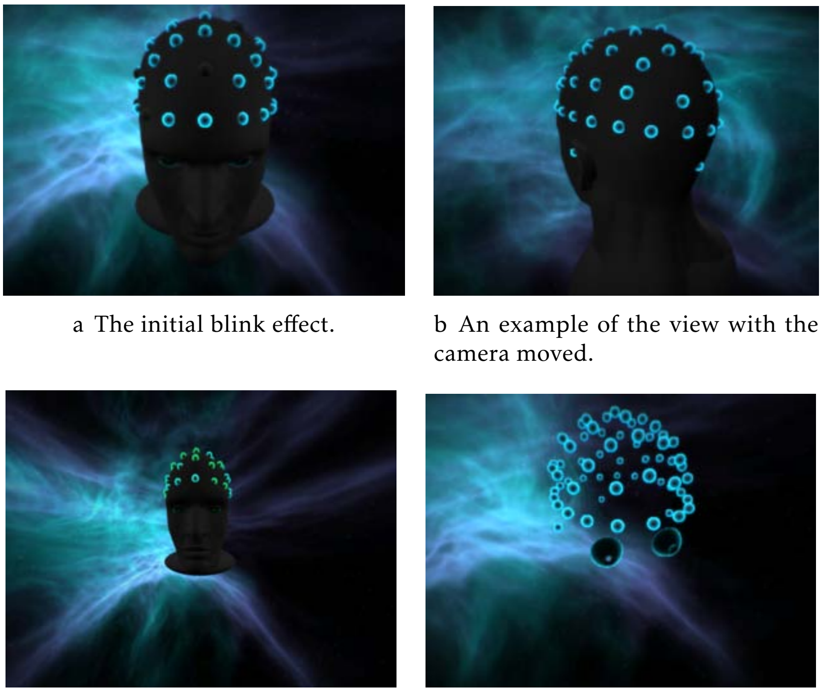
The result of this project lies in two executable files: A desktop application for Windows® and an Oculus®DK1 application also for Windows®. These applications allow the user to undergo an immersive, NFB experience, in a digital environment.

Table 5.1 exhibits the list of commands.

Keys	***Effect***
"Esc"	Opens the main menu
"Enter"	Plays the loaded file
"S"	Stops the playing file
Arrow Keys	Control the camera movement
"1"	Activates File Reading Mode
"2"	Activates Live BCI Mode
"F"	Loads the file with the inserted name
"Space"	Shifts the current music
"M"	Mutes the environment
"H"	Calls the help menu

Table 5.1: Description of the available commands in the application.

The environment opens with a blinking visual effect and in default File Reading Mode. The user is able to load a file into the program, to analyse it, to activate "ghost mode", to shift through soundtracks and to shift into Live BCI Mode, in which he can then select the type of data he wants to read from his MindBand BCI. Figure 5.1 exhibits some of these functionalities.



a The initial blink effect.

b An example of the view with the camera moved.

c The Oculus DK1 view.

d The "ghost mode" functionality.

Figure 5.1: Several aspects of the developed application.

5.2 Neurofeedback testing

To test the application according to the method described throughout section 4.2.7, five subjects were selected for the control group and five other subjects for the study group. All of the subjects fulfilled the conditions detailed in section 4.2.7.

The results are represented through tables 5.2 and 5.3.

Subjects	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Age	23	24	21	22	19
Sex	M	F	M	M	M
Words read in book 1	304	279	290	379	271
Words read in book 2	285	294	290	354	270
Difference in words read	-19	+15	0	-25	-1
Percentage of words read in book 2 regarding book 1	-6.3%	+5.4%	0%	-6.6%	-0.4%

Table 5.2: Results obtained from the control group.

Subjects	Subject 6	Subject 7	Subject 8	Subject 9	Subject 10
Age	25	22	24	21	22
Sex	M	F	M	M	M
Words read in book 1	254	760	527	458	445
Words read in book 2	222	614	489	391	343
Difference in words read	-32	-146	-38	-67	-102
Percentage of words read in book 2 regarding book 1	-12.6%	-19.2%	-7.2%	-14.6%	-22.9%

Table 5.3: Results obtained from the study group.

The results seemingly point towards the existence of an alteration in the Attention factor of the subjects encased in the study group. This alteration manifests, as expected, as a slower pace of reading throughout the second book, when compared to the reading pace of the first book.

These results could presumably confirm the existence of NFB training in the application; however, to effectively do so this study would have to be applied to a much larger number of subjects, and its results statistically analysed. Therefore, the only claim possible to ensue from these results is that preliminary tests seem to indicate the presence of effective NFB training in Attention.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Through the development of the environment detailed along the latter chapters, the objective of the thesis was successfully achieved; a NFB training application was created for the Oculus® Rift DK1 and Neurosky®'s MindBand; both of these equipments are relatively affordable when compared to the price of typical NFB integrated systems available in the market.

Besides allowing the user to analyse his current mental state in VR, the program also allows the user to access data from .edf files, a supplementary function in comparison to the originally intended. The program can also run in a desktop, although the level of immersion will be consequently diminished.

However, to actually apply the environment in psychotherapy, the level of NFB effectiveness needs to be ascertained by subjecting a large number of users to extensive testing; furthermore, to provide reliable NFB, the environment needs to support a broader range of BCI devices, since the MindBand possesses a crippling limitation: It has only one EEG channel.

The unavailability of hardware presented a difficulty at times; this problem occurred since various students in the IBEB were concurrently developing their thesis. Access to a more recent version of the Oculus Rift®, for example, could have contributed to the quality of the immersive output of the program.

6.2 Future Work

Apart from the extensive testing mentioned in the latter chapter, there is a broad diversity of possible increments to this application, both in the form of hardware as in the form of software.

The VR support could be extended to the DK2 and to the Consumer Version 1 (CV1), and even to other VR products, such as the HTC Vive®;

The BCI support could also be expanded to other products, such as the EMOTIV® EPOC, which possess more channels and hence more EEG information. Even though initial development of such a feature happened, the lack of available tools for connectivity between EMOTIV® and Unity® led to the abandonment of the idea for the thesis;

The implementation of a sensor device that supports hand and finger motions as input, such as LeapMotion®, would add to the immersive experience of the environment. Figure 6.1 exhibits an adapter for the LeapMotion® device to be used conjointly with the DK1, developed in the IBEB;

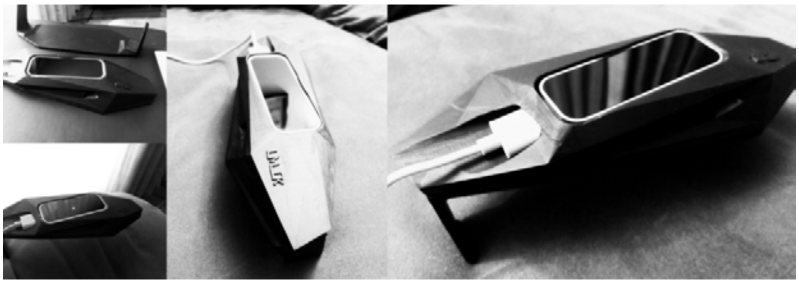


Figure 6.1: A LeapMotion® adapter, developed in the IBEB for the DK1 HMD.

Regarding the software component, some ideas for future implementations:

- An .edf file creator, in order to record selected segments of the Live BCI Mode;
- A Pause command, which would temporarily pause the stream of information flowing to the electrode objects during the File Reading Mode;
- An UI which would exhibit a graphical representation of the transmitted electrode data, over a time period.

Hopefully the output of this project will constitute a step in achieving a VR-embracing reality, where common, day-to-day VR displays are present in everyday live and daily use of VR applications such as the one developed along this project is a common practice. Being able to monitor self brain activity by the end of the day to realize just how stressful the day has been, or checking upon the mental state achieved after practising intense physical activity can now make part of the daily routine of the common denizen of the future society, by means of a user-friendly, affordable, immersive environment.

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Appendix A

Spatial Coordinates of the Electrodes

Electrode	X	Y	Z	Electrode	X	Y	Z
Fp1	-0.674	1.358	2.172	FC6	1.6	1.95	0.549
Fpz	0	1.4	2.4	FT8	1.7	1.232	0.54
Fp2	0.655	1.358	2.23	T9	-1.8	0.3	-0.1
AF7	-1.16	1.316	1.78	T7	-1.77	1.19	-0.14
AF3	-0.6	1.99	1.95	C5	-1.7	1.95	-0.18
AFz	0	2.2	2.05	C3	-1.35	2.63	-0.22
AF4	0.6	1.99	1.95	C1	-0.73	3.025	-0.26
AF8	1.16	1.316	1.78	Cz	0	3.18	-0.3
F7	-1.5	1.274	1.19	C2	0.73	3.025	-0.26
F5	-1.33	1.85	1.28	C4	1.35	2.63	-0.22
F3	-1	2.3	1.37	C6	1.7	1.95	-0.18
F1	-0.55	2.65	1.4	T8	1.77	1.19	-0.14
Fz	0	2.8	1.4	T10	1.8	0.3	-0.1
F2	0.55	2.65	1.4	TP7	-1.75	1.148	-0.82
F4	1	2.3	1.37	CP5	-1.66	1.9	-0.91
F6	1.33	1.85	1.28	CP3	-1.3	2.52	-1
F8	1.5	1.274	1.19	CP1	-0.73	2.9	-1.09
FT7	-1.7	1.232	0.54	CPz	0	3.05	-1.18
FC5	-1.6	1.95	0.594	CP2	0.73	2.9	-1.09
FC3	-1.25	2.55	0.558	CP4	1.3	2.52	-1
FC1	-0.73	2.9	0.567	CP6	1.66	1.9	-0.91
FCz	0	3.1	0.575	TP8	1.75	1.148	-0.82
FC2	0.73	2.9	0.567	P7	-1.56	1.106	-1.48
FC4	1.25	2.55	0.558	P5	-1.46	1.76	-1.59

Table A.1: Spatial coordinates of the electrode objects.

Electrode	X	Y	Z
P3	-1.15	2.25	-1.7
P1	-0.6	2.51	-1.85
Pz	0	2.6	-1.94
P2	0.6	2.51	-1.85
P4	1.15	2.25	-1.7
P6	1.46	1.76	-1.59
P8	1.56	1.106	-1.48
PO7	-1.26	1.064	-2.05
PO3	-0.75	1.6	-2.35
POz	0	1.85	-2.42
PO4	0.7	1.65	-2.35
PO8	1.26	1.064	-2.05
O1	-0.67	1.022	-2.47
Oz	0	0.98	-2.6
O2	0.67	1.022	-2.47
Iz	0	0.12	-2.45

Table A.2: Spatial coordinates of the electrode objects.