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LOPES DE SOUSA

Software for processing EEGs to calculate the amount of information transferred between channels using the Granger algorithm

Software para o processamento de EEGs para o cálculo da quantidade de informação transferida entre canais usando o algoritmo de Granger

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" *The first step in solving any problem is recognizing there is one.*"

— Aaron Sorkin

Universidade de Aveiro
2023

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Projeto final de licenciatura apresentado à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Licenciatura em Engenharia Biomédica, realizada sob a orientação científica do Professor Doutor Miguel Pais Vieria, Professor auxiliar em regime laboral do Departamento de Física da Universidade de Aveiro, e do Professor Doutor Carlos Alberto da Costa Bastos, Professor auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro

.

Dedico este projeto às pessoas que foram mais importantes na construção do meu percurso académico, nomeadamente à minha família, que sempre me apoiou, ajudou, motivou e ensinou a ser o melhor e a conseguir o melhor de mim mesmo, sem eles nada disto seria possível.

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Palavras Chave EEG, Causalidade de Granger, Software, BCI, BVA, MATLAB, Off-Line

Resumo

Quando falamos de neurociência, temos de abordar um problema específico, como por exemplo, desvendar os mistérios de como os padrões complexos da atividade elétrica cerebral codificam as informações dos estímulos sensoriais e a sua atividade elétrica do sistema nervoso. Um dos muitos procedimentos para resolver este problema está relacionado com o estudo do papel funcional das ondas corticais. Estas ondas cerebrais são tipicamente reconhecidas pelos seus padrões oscilatórios, que facilitam a sincronização de muitos neurónios em múltiplas escalas espaciais e temporais, dependendo do seu mecanismo e função biológica.
Vários estudos anteriores, experimentais e computacionais, também aplicaram a Causalidade de Granger como medida de transferência de informação, e mostraram que as áreas corticais, quando se dedicam a tarefas específicas, podem auto influenciar-se mutuamente através de ondas corticais.
O eletroencefalograma, um exame não invasivo e com boa capacidade de captar um evento no momento exato em que este ocorre, tem servido como ferramenta para analisar a atividade cerebral sob a forma de ondas. O seu estudo pode elucidar questões sobre como o processamento da informação sensorial acontece e chega ao cérebro, bem como ajudar a mapear a auto interação entre diferentes regiões corticais.
O seguinte projeto visa desenvolver um software melhorado de Interface Máquina-Computador (BCI, *Brain-Computer Interface*), onde qualquer utilizador pode carregar o seu sinal EEG e analisar a relação entre canais bidirecionais com um teste de causalidade. O sinal será adquirido utilizando um ActiCAP com 16 elétrodos e um V-Amp para amplificar e filtrar o sinal. Em seguida, o utilizador pode descarregá-lo do *Brain Vision Analyzer* (BVA) e introduzi-lo no software para ser analisado. O software consiste em converter os sinais EEG para MATLAB, extrair a frequência de potência e efetuar um teste de causalidade baseado no algoritmo de Granger, onde é possível inferir sobre a sua nulidade.
A versão final deste módulo será conduzida a diferentes níveis de complexidade, incluindo:

- transferência de informação;
- cálculo de rácios de frequências;
- extração automática de redes neuronais com base na quantidade de informação transferida;
- análise da relação entre a quantidade de informação e a tarefa específica do comportamento de ação do sujeito

No que diz respeito às desvantagens, são reconhecidas algumas limitações, como o facto deste software não aplicar a causalidade de Granger à informação transferida via On-Line, algo a ter em consideração em próximos estudos.
Por último, pretendemos desenvolver um módulo funcional para a informação transferida Off-Line que possa ser incorporado num software, que poderá ser melhorado em futuras versões para análise em tempo real (On-Line).

Keywords EEG, Granger Causality Software, BCI, BVA, MATLAB, Off-Line

Abstract

When we talk about neuroscience, we must approach a specific problem such as unravelling the mysteries of how the complex patterns of the electric brain activity code sensorial stimulus information and their self-electric activity of the nervous system. One of many procedures to solve this problem is related to the study of the functional role of cortical waves. These brain waves are typically recognised by their oscillatory patterns, which ease the synchronisation of many neurons on spatial and temporal multiple scales, depending on their mechanism and biological function.

Several previous studies, experimental and computational, also applied the Granger Causality as a measure of transferred information and showed that cortical areas, when holding to specific tasks, could mutual self-influence through cortical waves. The electroencephalogram, a non-invasive exam with a good ability to capture an event at the exact moment when it occurred, has served as a tool for analysing brain activity under waveforms. Studying this may elucidate questions about how sensorial information processing happens and reaches the brain, as well as helping to map the self-interaction between different cortical regions.

The following project aims to develop an improved Brain-Computer Interface (BCI) software, where any user can upload his electroencephalogram (EEG) signal and analysis the relationship between bi-directional channels with a causality test. The signal will be acquired using an ActiCAP with 16 electrodes and a V-Amp to amplify and filter the signal. Then the user can download it from the Brain Vision Analyser (BVA) and introduce it into the software to be analysed. The software consists of converting EEG signals into MATLAB, extracting the frequency power and running a causality test based on the Granger algorithm, where it is possible to infer its nullity.

The final version of this module will be led to different levels of complexity, including:

- Transferring information
- Calculating frequencies ratios
- Extracting neural networks automatically based on the amount of transferred information
- Analysing the relationship between the amount of information and the specific task of action behaviour of the subject

Regarding disadvantages, there are some limitations recognisable, such as the fact of this software do not Granger cause the transferred information via On-Line, something to be taken in consideration on next studies.

Lastly, we intend to develop a functional module for transferred information Off-Line that can be incorporated into the software, which could be enhanced into better future versions for real-time analysis (On-Line).

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Glossary

GC	Granger Causality
MEG	Magnetoencephalography
EEG	Electroencephalography
ECoG	Electrocorticography
fMRI	Functional Magnetic Resonance Imaging
BCI	Brain Computer Interface
NS	Nervous System
Cl^-	Chloride ion
K^+	Potassium ion
Na^+	Sodium ion
ATP	Adenosine Triphosphate
FFT	Fast Fourier Transform
Ca^{2+}	Calcium ion
AD	Alzheimer's disease
PWE	Epilepsy
SCZ	Schizophrenia
BVA	Brain Vision Analyzer (version 2.2.1, Brain Products, Gilching, Germany)
MATLAB	Matlab (Mathworks, 2018b, Natick, MA, USA)
IIR	Infinite Impulsive Response
VR	Virtual Reality
FCT	Foundation to Science and Technology
PhD	Doctorate of Philosophy
fNIRS	Functional Near-Infrared Spectroscopy

CHAPTER 1

Introduction

This study will computationally approach the neuroscience field by using an improved BCI module and developing a software analysis module for EEG signals, applying the Granger Causality algorithm. To begin, I will describe some procedures for neuronal signal analysis, and then I will enhance the transferred information between different channels. Therefore, nervous system concepts, neuronal activity recording techniques, as well as their advantages and disadvantages will be also pointed out. It will be given a special observation about the EEG technique, there will be explained the recording stages, pre-processing and especially the processing. To deeply understand the importance of the implemented algorithm related to neuronal activity I will, further, detail the Granger algorithm. Then, the general and specific objectives of this project will be presented.

The analysis of neuronal network signals has been studied for several previous works, such as the "Study of theta and alpha bands of the electroencephalogram during arithmetic writing tasks" [1]; the "Processing of EEG signals for motor task classifications in Machine-Brain Interface systems" [2]. Regarding the transferred information between different channels while applying a causality test, with Granger algorithm, also has some notorious previous studies, such as the "Prediction of epilepsy seizure from multi-channel electroencephalogram by effective connectivity analysis using Granger causality and directed transfer function methods" [3]; "Neurophysiological correlates of tactile width discrimination in humans" [4]. Studying and analysing how the Granger causality test infers the amount of information transferred between different channels, bi-directionally, gives a state-space interpretation in which relations between measured variables and input variables are mediated via unobservable state variables [5]. In practice, G-causality may be one of the easiest algorithms to apply because of (i) the lack of explicit forward models and (ii) increased latitude concerning the number of variables incorporated [6].

In this study, it was developed a software analysis module, where EEG signals from BVA or MATLAB could be uploaded. There are many functionalities related to this software

module, which consists of automatically converting BVA signals to MATLAB, its analysis of the power frequency in terms of the different frequency bands, for every single channel, giving the users all the information and characteristics of the uploaded signal and, finally, Granger causes, bi-directionally, the amount of information transferred between all of the existing channels. The main goal was precisely to build a software for a specific task, where any EEG signal could be analysed and tested with a causality algorithm for different channels. Before initiating a detailed description of this project, first I will enumerate some concepts and techniques to fully understand this study.

The nervous system, described in the work of Ramón y Cajal, which consist of about one hundred billion neurons interconnected to form functional neural networks [7], allows us to understand more about the neuronal activity and its mechanisms, such as neuronal conductivity; electric potential; and synapses.

In addition, more advanced methods, such as graph theory, are commonly used to show the functional organisation of the brain as a fully complex network in which neuronal units are intimately coupled with one another via various direct and indirect paths [8], [9], [10].

Mapping the complexity of these interactions requires the use of high-resolution neuroimaging techniques [10], [11], where some of which are briefly described in the table below (table 1.1).

TECHNIQUE	ADVANTAGES	DISADVANTAGES	REFERENCES
Functional Magnetic Resonance Imaging (fMRI)	High spatial resolution Non-invasive Lack of radiation Fast	Only implemented on sleep Low temporal resolution Expensive Stillness patients	[12]
Electrocorticography (ECoG)	High spatial resolution High temporal resolution Intracranial recordings are not susceptible to artifact contamination	Invasive Limited sampling time Limited field of view	[13]
Electroencephalography (EEG)	High temporal resolution Non-invasive Fast Cheap	Low spatial resolution Useless in source pin-pointing Wave forms indistinguishable	[14]
Magnetoencephalography (MEG)	Direct measure of brain function High temporal resolution High spatial resolution Non-invasive Complementary tool	Highly sensitive instrumentation and sophisticated methods for eliminating environmental magnetic interference	[15]
Functional Near-Infrared Spectroscopy (fNIRS)	Non invasive High temporal resolution Awareness implementation	Ease light diffusion Low spatial resolution	[16]

Table 1.1: Neuronal activity recording techniques - advantages and disadvantages

While fMRI is the most widely-known technique for analysing brain activity, other technologies provide unique perspectives on the synchronised activity of spatially localised brain networks [17], [18]. However, EEG has been used in a wide range of clinical and research applications, allowing researchers to identify the spatial-temporal patterns of neuronal electric activity over the scalp with great ease, thanks to advances in acquisition technologies such as the development of high-density EEG systems and their combinations with other imaging modalities, robotics, or neurostimulation [19], [20], [21].

As I mentioned before, this study evolves EEG techniques, which have many types of analysis, such as energy, power, frequency, phase and module. Also, this can provide knowledge about neuronal activity, which is linked to the information analysed.

At last, there is the Granger causality algorithm, which will be described mathematically. In terms of linear regression modelling, this algorithm was introduced by Granger in 1969. According to G-causality, X2 causes X1 if the inclusion of past observations of X2 reduces

the prediction error of X1 [22]. Therefore, when tested between different channels of an EEG, it gives a statistical evaluation, despite being considered as an exploratory rather than confirmatory approach to discerning directed functional connectivity as shown in the article "A MATLAB toolbox for Granger causal connectivity analysis [6]. This is because G-causality is permissive concerning structural constraints, typically making few if any assumptions about the causal connectivity patterns embedded in the data, such as the p-value and the hypothesis [6].

CHAPTER 2

A Concise Anatomophysiological Overview of the Human Brain

The brain is undoubtedly the most important structure in the human body, accounting for around 80% of the encephalon's total mass [23]. It is a complex organ that contains nearly one hundred billion neurons in adults, responsible for generating and transmitting electrical signals throughout our body [24]. These signals can be directly monitored or not, via an EEG, which records the electrical activity of the brain [23]. This data can then be harnessed by sophisticated software as known as Brain Computer Interface (BCI) systems, which trace a person's intentions and generate the corresponding output signal [23]. To understand this process better, it is crucial to study the anatomical organisation and physiology of the human nervous system [23]. With the right knowledge, we can decipher how BCI systems work and how they can be optimised to aid individuals with neurological disorders to communicate more efficiently [23].

The brain is divided into two hemispheres (left and right), separated by the inter-hemispheric fissure and connected by the corpus callosum [23]. Its grey matter, represented by the cerebral cortex (figure 2.1), is made up of billions of neuron bodies [23]. A layer of white matter lies beneath this, mainly composed of bundles of myelinated axons [23]. Each hemisphere contains four distinct lobes: occipital, parietal, frontal and temporal, each having its specific functions [23].

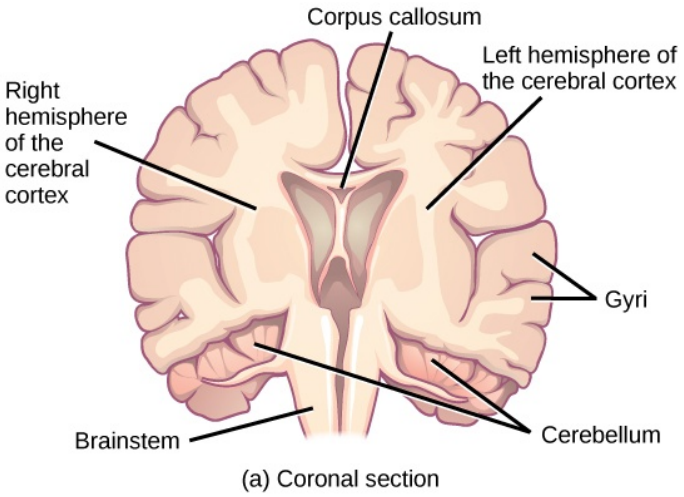


Figure 2.1: Coronal section of the cerebrum [25]

2.1 Nervous System

The Nervous System (NS) is composed of two types of cells: glial cells and nerve cells (neurons) [24]. Glial cells are responsible for sustaining, nourishing, protecting, and insulating the neurons [24]. On the other hand, neurons play a highly specialised role in generating bioelectrical signals, which are triggered by the imbalance of ions in the intracellular and extracellular environment [23]. These signals are transmitted throughout the body to alert us to various stimuli, both internal and external, and enable our body to respond accordingly [23].

The structure of nerve cells may vary in shape and size, but their composition remains constant as shown in figure 2.2 [25]. These cells consist of three main parts, namely the cell body, dendrites, and axon [26].

The dendrites are extensions that are branched and form connections with adjacent neurons, receiving stimuli and serving as the primary entry point for information into the neuron towards the cell body [24]. In contrast, axons are unique structures in each neuron, with a relatively large cylindrical shape that is capable of terminating in other effector organs or neurons through small branches that end in a particular dilatation called terminal buttons [24]. Their primary function is to transmit impulses out of the cell body generally [26].

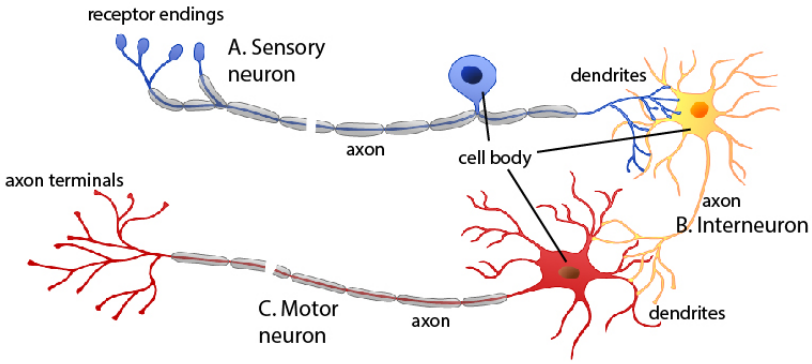


Figure 2.2: Typical neurons of a mammal [25]

2.2 Electric Potential

The nervous system's operations rely on the excitability of neurons, which is linked to the characteristics of their inactive state (when there is no nerve impulse) [26].

When a neuron is at rest, it generates an electrical potential by maintaining an ion gradient across its plasma membrane [26]. To comprehend the resting state and electrical potential, it is crucial to grasp how the resting membrane potential is established, which refers to the variation in electrical charges across the membrane [26].

The fluid inside and outside the neuron is mainly made up of water and contains electrically charged atoms called ions [26]. These ions, specifically the positively charged Sodium ion (Na^+), cation, and negatively charged Chloride ion (Cl^-), anion, are responsible for the neuron's resting and action potentials [23]. Potassium ion (K^+) another positively charged ion, is also critical for proper neurophysiological function [24]. It is essential to consider all of these components when studying the fluid and ions present in and around neurons [26].

Additionally, the phospholipid bilayer plays a crucial role in separating the intracellular and extracellular medium and allowing the transport of ions, specifically potassium ions when at rest [27]. This bilayer includes intrinsic proteins that form ion pumps, which enable the transport of ions between the media and are related to the resting and action potentials [27]. These ion pumps use the energy released from breaking down Adenosine Triphosphate (ATP) (current energy of the cells) [27].

When a neuron is stimulated, it allows for the entry of Na^+ into the cell due to increased membrane permeability [27]. This results in depolarisation, a change in membrane potential from -70mV to +30mV, which excites the neuron and leads to the electrical action potential of the membrane [27]. This potential is then transmitted across the plasmatic membrane [27].

The resting membrane is sensitive to changes in extracellular potassium concentration and is permeable to potassium ions (figure 2.3) [28]. After depolarisation, repolarisation occurs due to a rapid efflux of potassium ions, returning the membrane to its resting state [28].

However, if there is a delay in the closing of potassium channels, it can result in membrane hyperpolarisation [28].

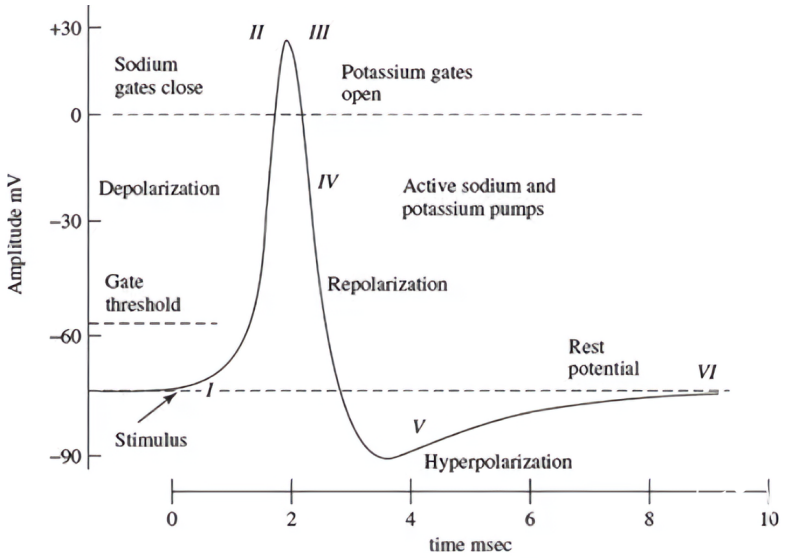


Figure 2.3: Change in neuronal membrane potential due to neuronal membrane ion exchanges [28]

The nerve impulse, which is a potential generated by a specific part of the membrane, remains constant in size and duration throughout its conduction by the axon [29]. The frequency and pattern of this potential hold specific characteristics that neurons use as a code to transfer information between different areas [29]. Once the neuron is no longer stimulated, the sodium-potassium pump restores the ions' concentrations in both the intracellular and extracellular regions [29].

2.3 Cell to Cell Transmission - Synapses

The axon branches are situated near the adjacent dendrite cell [23]. However, a narrow gap separates them, which is less than 1/1000 centimetres wide, called the synaptic cleft [23]. The transmission of impulses occurs through chemical substances or electrically, via ion flow between neurons [24]. The synapse serves as a point of junction, where signals are transmitted from the pre-synaptic neuron terminal to the postsynaptic neuron terminal (figure 2.4) [24].

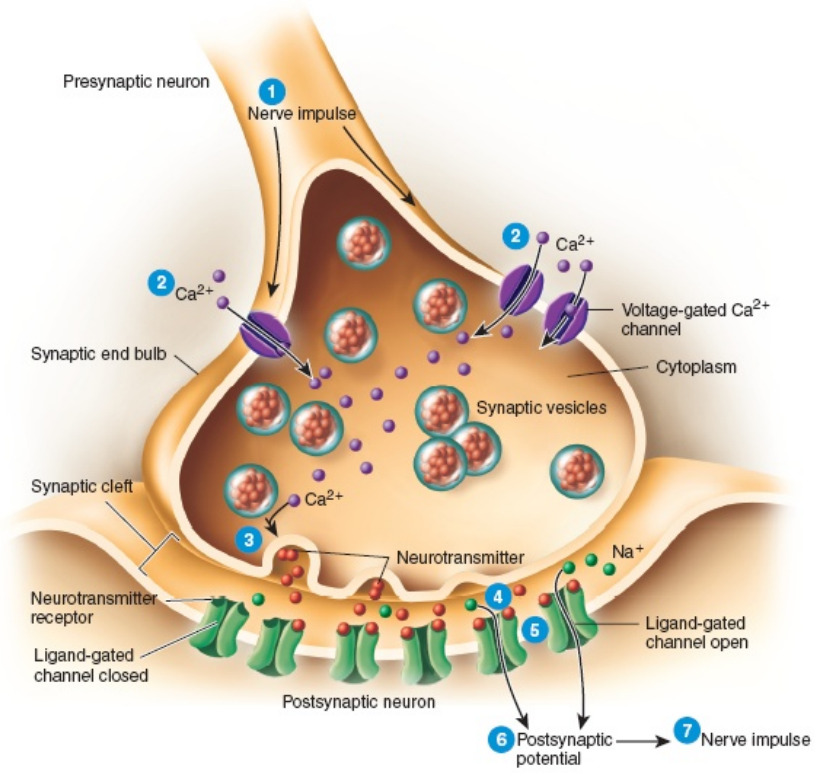


Figure 2.4: Impulse transmission across the synapse [30]

In chemical synapses, the entry of Calcium ion (Ca^{2+}), caused by depolarisation of the neuron terminal membrane, leads to the exocytosis of stored neurotransmitters in vesicles [24]. These neurotransmitters are then released into the synaptic cleft and bind to the postsynaptic neuron's membrane receptors [24].

Following this, an increase in the permeability of the postsynaptic neuron's membrane to Na^{+} is initiated, resulting in the generation of a new action potential in that particular cell (also known as an excitatory synapse) [24]. Conversely, inhibitory synapses hinder the transmission of nerve impulses by using neurotransmitters, reducing the cell's responsiveness [24]. Electrical synapses, on the other hand, transmit ion flow between cells, leading to the creation of an action potential in the postsynaptic neuron [24]. As a result, this method of communication is much faster and more efficient than the previous chemical synapses [24], on the other hand, electrical synapses only transmit depolarization signals [24].

CHAPTER 3

Electroencephalography - EEG

Electroencephalography is a widely used technique for measuring and amplifying electrochemical activity in the brain [31], also EEG is a method of low-cost and non-invasive imaging [32], [33]. It is capable of studying the vibrant connections between cortical brain area activity and gives varied details compared to fMRI [34]. The obtained information comes through non-invasive electrodes placed on the scalp, which record neurons' combined excitatory and inhibitory postsynaptic potentials [31]. These potentials create electric fields that can be measured by conductive electrodes placed on the scalp and aided by conductive gel to improve contact with the skin [31]. The placement of these electrodes follows the international 10-20 system configuration, which determines the distance ratio between the electrodes and reference points covering the entire brain (figure 3.1) [35].

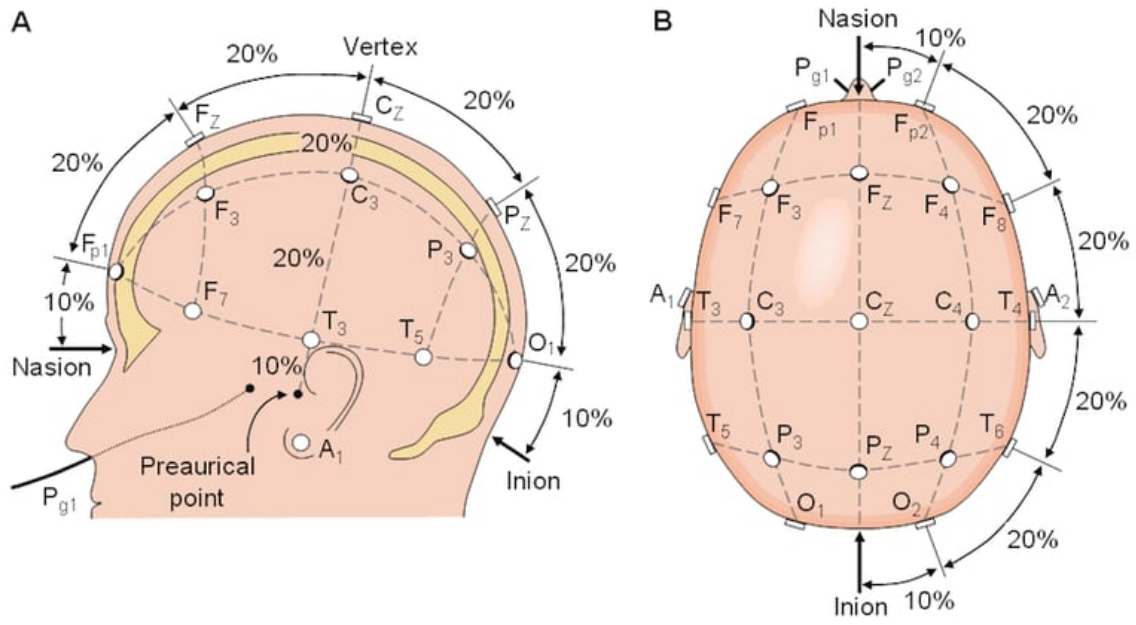


Figure 3.1: Representation of the positioning of the electrodes on the scalp according to the international 10-20 system [35]

To record the brain's electrical activity, electrodes are connected to an amplifier that matches the signal and removes overlapping noise [36]. In the past, this was done through a highly sensitive needle on paper, resulting in spatial limitations and limited frequency recording [36]. Today, EEG is digital, but the process of transforming analogue signals into digital ones for analysis presents some challenges [37]. Despite this, the brain's electrical activity analysis is still valuable in medical and clinical research [38].

To reconstruct the signal from a current EEG, the Fast Fourier Transform (FFT) is used, which is a digital signal processing tool that can analyse and design systems in the frequency domain [39]. This tool is effective because, despite the stationarity of the system, it provides good temporal resolution (equation 3.1) [39].

$$F[x(t)] = X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t}dt \tag{3.1}$$

Fast Fourier Transform [39].

The EEG records brain activity across different frequency bands, ranging from 0.05 Hz to 500 Hz, which can be categorised into low-frequency (delta, theta, and alpha) and high-frequency (beta and gamma) waves [37]. High-frequency waves are typically recorded during wakefulness, while low-frequency waves are more common during sleep [37]. However, there is currently no agreement within the scientific community regarding the specific frequency ranges for different wavebands [40]. To address this, in this project, I chose the following configuration: delta (0.5-4.5) Hz, theta (4.5-8.5) Hz, alpha (8.5-13-5) Hz, beta (13.5-30.5) Hz, and gamma (30.5-100) Hz (figure 3.2) (according to Pais-Vieira, Kunicki, Peres, *et al.* [41]). There are various factors responsible for the mismatch, but the primary reasons include the varying precision of EEG equipment and the distinct physiological features of individual brains [38].

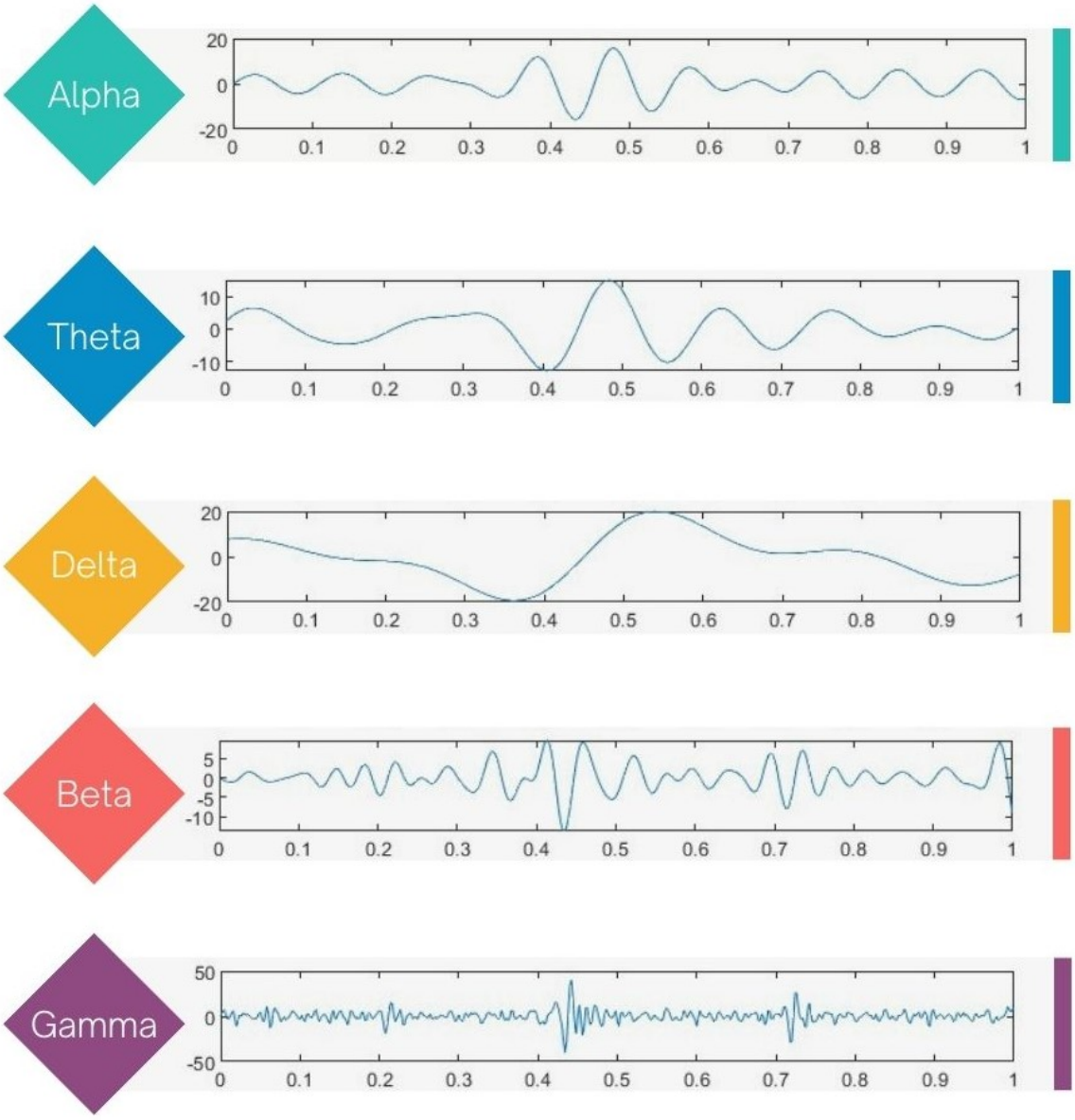


Figure 3.2: Brain rhythms during activity, when describable (Adapted and designed from the software)

CHAPTER 4

Brief introduction to Granger Causality Algorithmic - GC

Linear methods are employed to determine Granger Causality (GC), which is a measure of the causality of a time series [42]. The application of causality is significant in various scientific fields, particularly in neuroscience [42]. The estimation of the directional interaction between brain regions through neurophysiological recordings like EEG or ECoG can offer insights into numerous neurological disorders such as Epilepsy (PWE), Alzheimer's disease (AD), and Schizophrenia (SCZ) [43]. GC is a commonly used technique to establish this causality [43].

4.1 Fundamentals of GC

A process Y Granger causes X if it is possible to predict X more effectively when we incorporate information from the past time Y, using regressive linear modelling [44]. We can predict x(t) from the autoregression, relative to its past, equation 4.1 [42]:

$$X(t) = \sum_{i=1}^{\infty} \hat{a}_i X_{t-i} + \hat{\epsilon}_t, \tag{4.1}$$

where $\hat{a}_t$ is the autoregression coefficient and $\hat{\epsilon}_t$ is the prediction error [44]. If another observation Y is also available, then we can also try to predict x(t) (equation 4.2) [42]:

$$X(t) = \sum_{i=1}^{\infty} a_i X_{t-i} + \sum_{j=1}^{\infty} \hat{b}_j Y_{t-j} + \epsilon_t, \tag{4.2}$$

where a(i) and b(i) are the regression coefficient and ϵ_t is the prediction error [22]. The accuracy of a prediction improves with a decrease in the level of error [22]. Therefore, the GC of Y for X, which determines the correlation between Y and X to make predictions, is expressed through the equation 4.3 [42]:

$$F_{Y \to X} = \log \frac{Var(\hat{\epsilon}_t)}{Var(\epsilon_t)}, \tag{4.3}$$

which considers the variance of the errors when we only use the past time points of X and when we use the past time points of X and Y to predict x(t), respectively [22]. If the errors have a low variance, it implies that the regression coefficients are dependable and the prediction is accurate [22]. When we add the past time of Y to the equation and it enhances the prediction of X, the error variances ratio will be more than 1 and the logarithm value will be greater than zero [22]. If not, the statistic will tend towards zero [42].

CHAPTER 5

Methods

A general electroencephalography study is presented, where a patient was offered various sessions of BCI tests to retrain information about his brain activity during specific tasks.

5.1 Materials

The electroencephalographic recordings were acquired by an actiCAP made from 16 channels at 1,000 Hz using a 10-20 placement.

Despite recent improvements in EEG and electrode technology, most research applications still require low skin impedance levels [45]. In EEG combined with other technologies, such as EEG and fMRI, impedance level multiplies with artefact amplitude, quickly obscuring any EEG signal, so impedances should be kept as low as possible [45]. Therefore, to achieve low impedances we needed to abrade the area of skin underneath each electrode and then apply an electrolytic gel [45].

Furthermore, for accommodating, amplifying and converting the analogue electric EEG signals into digital ones, which could be processed by the computer software, it was used a V-Amp EEG amplifier, which belongs to the part of the data acquisition system [46].

The signals, then, were recorded and visualised by the Brain Vision Analyzer (version 2.2.1, Brain Products, Gilching, Germany) (BVA) program (figure 5.1).

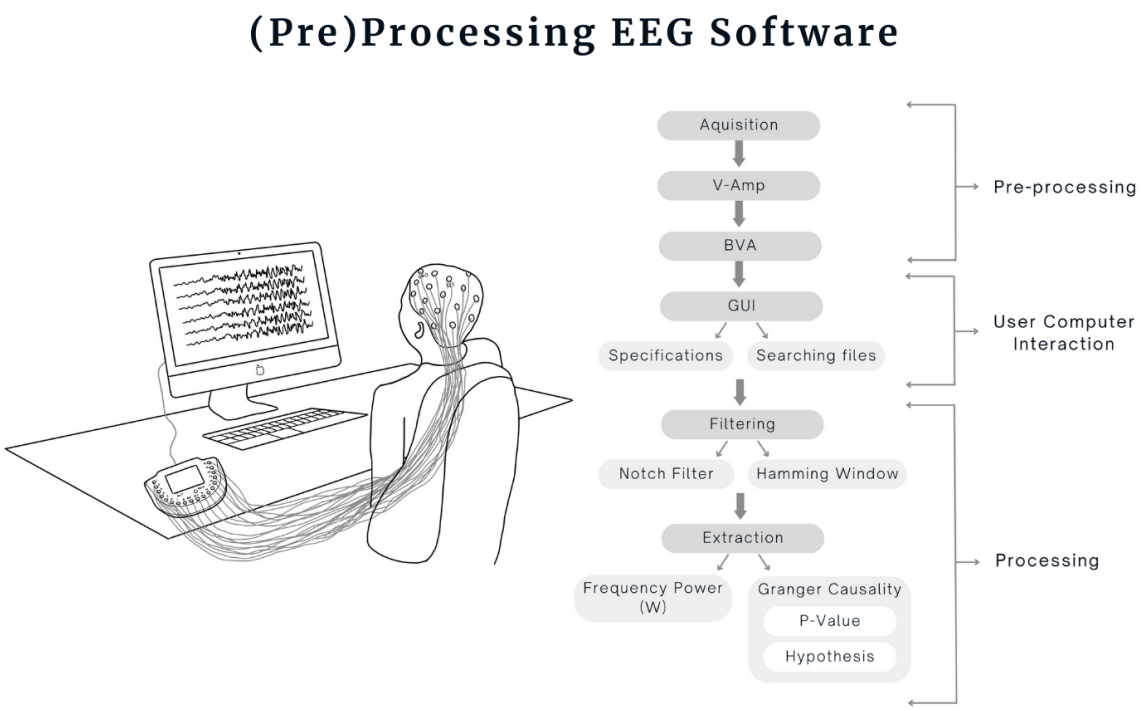


Figure 5.1: Procedure representation (Designed specifically for this project, by Sara Pombo, DeCA, UA)

5.2 Pre-Processing

After downloading the signal from BVA, the user can analyse it using the developed software, when running the application and pushing the " START " button.

When the signal is uploaded into the software, it first undergoes a format conversion process, from BVA to MATLAB, using the *BVA2Matlab* function, so that it can be analysed by the software.

The second step was to apply a MATLAB function *hamming window* to the signal, with the same length, to reduce the ripple on either extremity and give a more accurate idea of the original signal's frequency spectrum [47].

Sequentially, a notch filter (50 Hz) with zero-phase shift (using a MATLAB function, *filtfilt*), 4th order, Butterworth filter, a low cutoff frequency of 0.5 Hz and high cutoff frequency of 70 Hz with a time constant of 0.3183 was applied to the signal.

The remaining signal was normalised (frequency response) after each applied filter, including the notch filter, and analysed in terms of frequency bands: delta (0.5–4.5) Hz, theta (4.5–8.5) Hz, alpha (8.5–13.5) Hz, beta (13.5–30.5) Hz, and low gamma (30.5–45) Hz, using a Infinite Impulsive Response (IIR) filter, 6th order, Butterworth filter, with the respectively low and high cutoff frequencies (according to Pais-Vieira, Allahdad, Perrotta, *et al.* [4]).

5.3 Frequency Power

To extract the frequency power, the software first extracts the energy of the filtered signals using the moving window method, which consists of segmenting the signals into temporal windows, and for each one, it calculates the energy, equation (5.1). It then moves to the next time window and goes half of it backwards to minimise possible errors, using the overlap method.

$$E(x) = \sum_{i=1}^{\infty} |x(i)|^2, \tag{5.1}$$

Finally, it starts to extract the mean frequency power, equation (5.2) of each segment for each channel, for each stimulus for all different band frequencies.

$$P(t) = \frac{E}{\Delta t}, \tag{5.2}$$

5.4 Granger Causality

Granger causality was used to investigate bi-directional connectivity between different channels (Granger, 1969). Before running the causality test, the signals were pre-processed using the same procedure mentioned before and tested in every possible direction. The evaluation of the Granger Causality test was made from the Matlab function *gctest*, which takes the amount of the signal information of all different stimulus and do a causality test between different channels, giving the hypothesis test (where "H=0" means a rejection hypothesis of the analysing channel's pair on being, either way, cause of each other and "H=1" means it was not rejected that hypothesis) and the p-Value test (when closer to zero the more accurate is the test), for the same frequency band, using α equal to 0.05, by default.

CHAPTER 6

Results

This chapter will mention the results that the software presented, such as the usability to users with minimum experience and knowledge of working with other application devices, and also which specifications this software includes and its functionalities.

6.1 App's Graphic Perception

The first interface that my software showed is called **SPECIFICS** (figure 6.1.**A**) which presented the signal **CHANNELS** (figure 6.1.**B**), **STIMULI** (figure 6.1.**C**) and **SAMPLING FREQUENCY** (figure 6.1.**D**). On the same "page", before pressing the button **START** (figure 6.1.**E**), for running the program, the user needed to choose the length of the temporal **WINDOW** (figure 6.1.**F**) and then the **OVERLAP** value (figure 6.1.**G**), in seconds, allowing the software to segment the signal, before extracting any information.

Additionally, there was a drop-down box named **CHOOSE OBSERVATION** (figure 6.1.**H**), which contained many options, some about the analysis of the extracted frequency power, others about the Granger Causality test. When choosing one of the observations, automatically it presented a table on the "second page", called **RESULTS**, (figure 6.1.**I**).

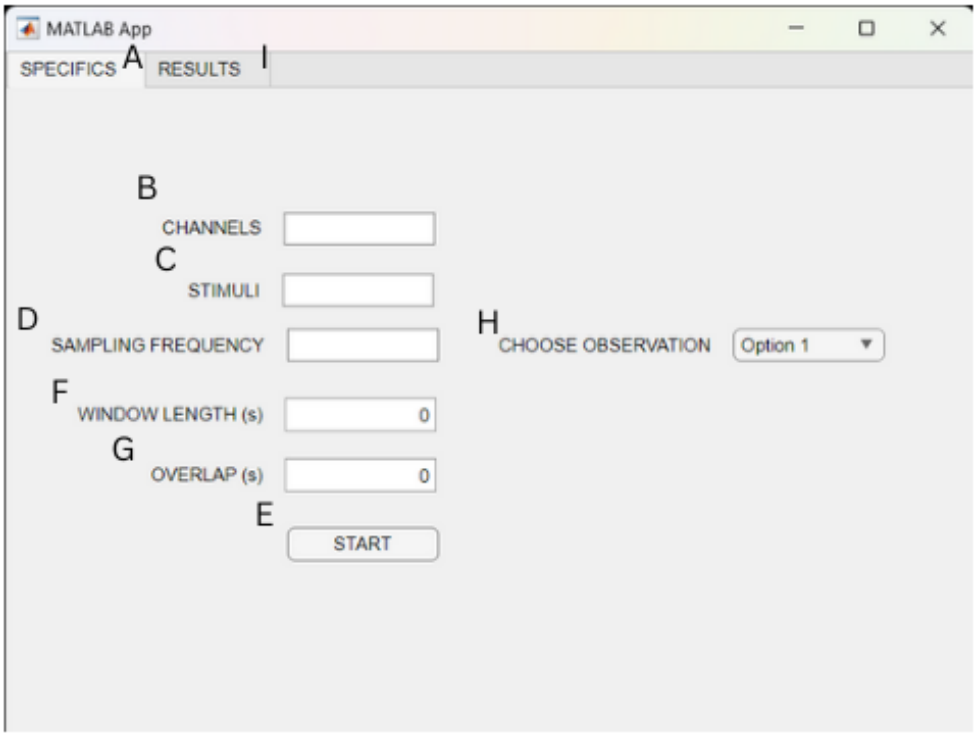


Figure 6.1: Software interface perception (Adapted from the software results)

6.2 App's Functionalities

The software has many functionalities, such as: Searching files; (Pre)Processing; Extracting and analysing the percentage of the power of each channel between different frequency bands during all stimuli and also between different stimuli for all frequency bands; Extracting and analysing for each stimulus the Granger Causality test between different channels for the same frequency band.

6.2.1 Searching Files

Once the user chooses the temporal **WINDOW** and **OVERLAP** length, and presses the button **START**, the software program runs the Matlab function *uigetfile* and shows a searching place for the user to select the pretended EEG file, that was already downloaded from the Brain Vision Analyzer (version 2.2.1, Brain Products, Gilching, Germany).

6.2.2 (Pre)Processing

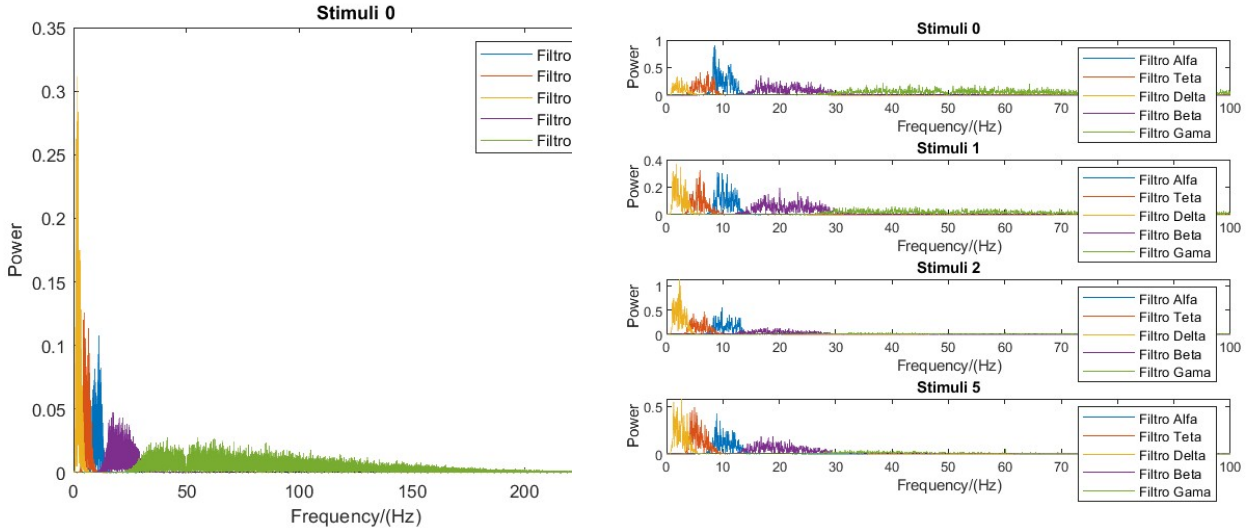
After the signals was uploaded to the software it will suffer a converting process applying a Matlab function called *BVA2Matlab*, which will provide the recorded signal with the ability to be analysed by the software.

The first filtering step was to apply a notch filter (50 Hz) with zero-phase shift (using a MATLAB function *filtfilt*), 4th order Butterworth filter, a low cutoff of 0.5 Hz and high cutoff of 70 Hz with a time constant of 0.3183 were applied to the signal.

The remaining signal was normalised (frequency response) after each applied filter, including the notch filter, and analysed in terms of frequency bands: delta (0.5–4.5) Hz, theta (4.5–8.5) Hz, alpha (8.5–13.5) Hz, beta (13.5–30.5) Hz, and low gamma (30.5–45) Hz, using a IIR filter, 6th order Butterworth filter, with the respectively low and high cutoff frequencies [4].

6.2.3 Extracted Frequency Power

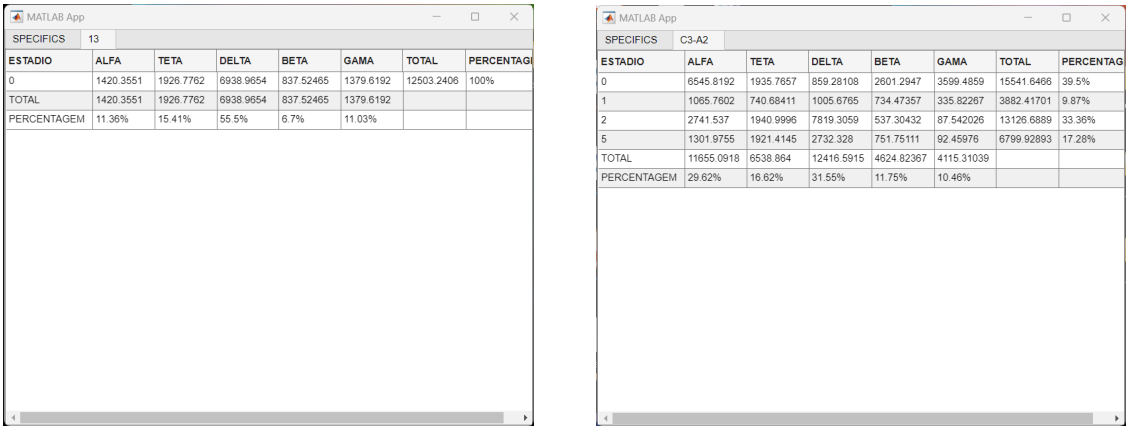
After extracting the frequency power, the software runs several figures equal to the number of existing channels. Each figure plots the frequency power of each channel for each stimulus, making a "hold on" for every frequency band evaluated (figure 6.2).



(a) **(b)**

Figure 6.2: Extracted frequency power from two tested examples, with 150 milliseconds of overlap and a 1000 milliseconds bandwidth: a) An arithmetic EEG signal; b) A sleep EEG signal, where there were four different stimuli, corresponding to each sleep stages of the signal (Both adapted from the software results)

Consequently, it analyses the frequency power percentage for each channel between different frequency bands during all stimuli and also between different stimuli for all frequency bands, inside of a table, in **RESULTS** (figure 6.3).



(a) **(b)**

Figure 6.3: Analysis of the extracted percentage frequency power for each channel from two tested examples, with the same specifications mentioned before: a) An arithmetic EEG signal; b) A sleep EEG signal with different sleep stages, corresponding to each stimulus (Both adapted from the software results)

6.2.4 Granger Causality Test Results

Finally, the software runs a Granger Causality test on the processed signal for each stimulus, where the amount of information between different channels is causally tested and analysed, giving the hypothesis test and the p-Value test, for the same frequency band (Table 6.1).

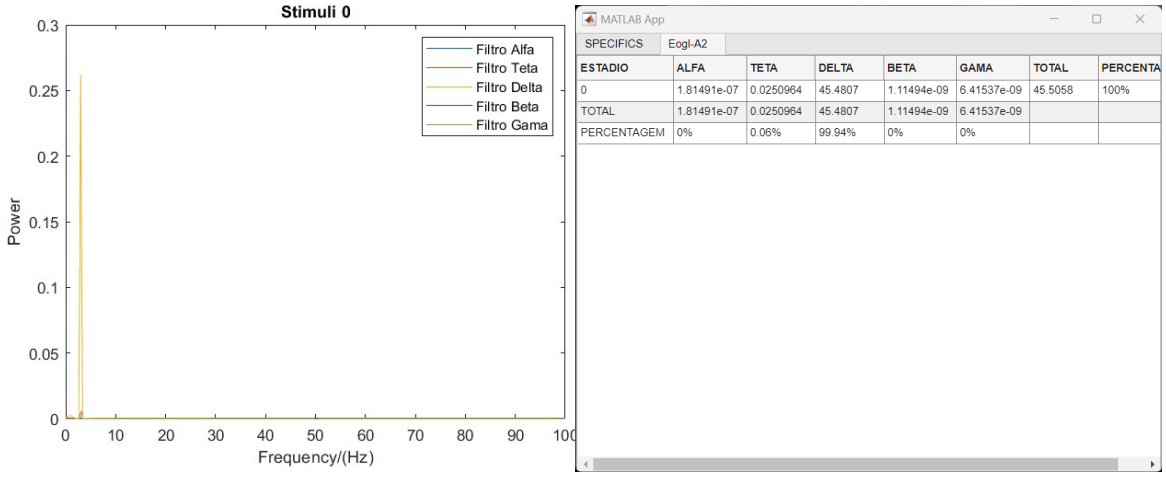
CHANNELS	HYPOTHESIS (H)	P-VALUE	BAND
Eogl-A2 & Eogr-A1	1	0	Alpha
Eogl-A2 & Eogr-A1	0	0.9238	Theta
Eogl-A2 & Eogr-A1	0	0.9918	Delta
Eogl-A2 & Eogr-A1	1	0	Beta
Eogl-A2 & Eogr-A1	1	0	Gamma
Eogr-A1 & Eogl-A2	1	0	Alpha
Eogr-A1 & Eogl-A2	0	0.8867	Theta
Eogr-A1 & Eogl-A2	0	0.9904	Delta
Eogr-A1 & Eogl-A2	1	0	Beta
Eogr-A1 & Eogl-A2	1	0	Gamma

Table 6.1: Granger Causality test applied, bi-directionally, to the channels of a verification test example, which is going to be discussed and described in the next chapter

CHAPTER 7

Discussion of Results

This study has developed a software for processing EEG signals to extract and calculate the amount of information transferred between channels using the Granger Causality algorithm. During this process, the software's final version was tested and verified. One of the verification test examples was a sinusoidal signal with two channels, running at 3 Hz. The software evaluated the percentage of power, giving the expected result. The delta frequency band has low and high cutoff frequencies of (0.5-4.5)Hz, so the total power should be at the delta frequency band, which was verified, with a precision of 99.96% (figure 7.1). The software relative error, 0.04% is due to the bandwidth chosen by the user.



ESTADIO	ALFA	TETA	DELTA	BETA	GAMA	TOTAL	PERCENTA
0	1.81491e-07	0.0250964	45.4807	1.11494e-09	6.41537e-09	45.5058	100%
TOTAL	1.81491e-07	0.0250964	45.4807	1.11494e-09	6.41537e-09		
PERCENTAGEM	0%	0.06%	99.94%	0%	0%		

(a) **(b)**

Figure 7.1: Analysis of the frequency power of one channel, for all frequency bands, with an overlap of 150 milliseconds and 1000 milliseconds of bandwidth, from a verification test example: a) Frequency power; b) Frequency power percentage (Adapted from the software results)

Additionally, the results demonstrated that the software was able to identify the main characteristics of the signal, such as *Channels*; *Stimulus*; *Sampling frequency*. Also, this software presented a percentage table and figures of the extracted frequency power for each

channel, between all frequency bands for all stimuli and applied the Granger Causality test for each stimulus, between all channels for the same frequency band, giving the Hypothesis and p-Value of the Matlab function *gctest*, that will be discussed further ahead.

7.1 First Result - GUI

The first software module interface, **SPECIFICS**, dispose of little boxes with specific names to identify some of the signal characteristics, which allow the user to know meaningful information about the analysed signal, such as which channels are being used, what stimuli or stimulus are being analysed and what sampling frequency are the signals being running in.

Furthermore, the second software module interface, **RESULTS**, exhibited a table which had information about the extracted and analysed information of the signal, respectively to what "chosen observation" the user selected, which can be about the extracted frequency power when choosing which channel or about the Granger Causality test when choosing which stimuli.

In comparison to other studies and projects, the graphic design and usability of this software appear to be much more practical and aesthetic, also it is directed to all users with minimum knowledge and experience working with other applications. However, it is required a minimum level of knowledge in neurophysiological signal analysing and interpretation, to be able to determine which are the best temporal windows and overlaps to use and the main characteristics of the applied filters, in pre-processing and during processing, and also a minimum level of statistical knowledge to be able to interpreter the Granger Causality test ran on the signals.

7.2 Second Result - Frequency Power Analyses

The developed software allows the analysis of the extracted frequency power for any EEG signal, with a MATLAB or a BVA format, for different frequency bands.

Virtually, every EEG analyse software runs the calculus of the frequency bands power. These analyses establish a connection between other previous works [4], [17], [11], [19], [20], [21], also triggers a bond with other possible future implementation measures, such as: (1) calculating frequencies ratios; (2) extracting neural networks automatically based on the amount of transferred information; (3) analysing the relationship between the amount of information and the specific task of action behaviour of the subject; (4) converting to an On-Line analysis module.

7.3 Third Result - Granger Causality Evaluation

Another functionality of the developed software is the ability of Granger cause the transferred information, bi-directionally [22], between different channels, for the same frequency band, and for each stimulus, giving the hypothesis test, where "H=0" means a rejection

hypothesis of the analysing channel's pair on being, either way, cause of each other and "H=1" means it was not rejected that hypothesis, also it gives the p-Value, when closer to zero, the more accurate is the test.

Other thesis and articles [4], [41], [42], [43], [44], also developed algorithms for analysing the transferred information between electrodes, mainly of EEG signals. Some were for Off-Line analyses [3], others for On-Line [48].

This software module, despite being an Off-Line study, has as its main goal to be, then, improved and upgraded to an On-Line analyse. The importance of this achievement plays with the necessity of improving the decodification of the BCI algorithm processing and giving to any user the possibility of running an EEG signal and extracting relevant information.

CHAPTER 8

Conclusion

The results of the developed software module indicated that was able to run any EEG signals, and shows its characteristics, by any user with minimum knowledge of how to work with other applications. Also, it can convert a BVA signal to a MATLAB one, filter, extract frequency power and perform the Granger Causality test, also suggests the necessity to improve to an On-Line analyse, and extract other meaningful signal information, as mentioned earlier.

On the other hand, this software module has some limitations related to the causality test, which despite being able to infer the causality of the transferred information between different channels, bi-directionally, can not, yet, calculate the frequencies ratios, or even infer the relationship between the amount of information and the specific tasks of the subject action behaviour.

Remembering now the verification test of the software functionalities, there is also a limitation embedded, which is about the relative error associated with the test, which is explained based on the bandwidth of the window length and on the overlap value, chosen by the user, which can always be altered and improved to a better one, however, it is important to acknowledged the specifications of the applied filters, which have a significant influence on the bandwidth, therefore the precision of the software.

Additionally, viewing future upgrades on better algorithms for BCI's implementation, it is necessary to improve this application to be used by more people with lower knowledge and turn it into a self-learning software and possibly a teaching one.

Previous software and thesis have already tried to implement the GC to analysed BCIs and EEGs [42], [43], [20], [21], [3], [48], however, those works had not implemented it into a general EEG signal. Besides that, the developed software was specifically designed to be applied on BVA and BCI sensory-motor experiences, which implies the use of Virtual Reality (VR), of an exoskeleton, touching stimulation, thermal, hearing and visual. Therefore, these multivariate types of variables result in a final approach quite more complex than what has been developed

and studied by other previous authors, and this work-study consisted of developing a software with the basics to achieve those goals, so the main objectives of this project were accomplished.

Furthermore, this project will always be linked to future works in this scientific field, and also, this software will be upgraded to an On-Line version, in my master's degree, where it will be possible to accomplish the previously mentioned goals and extinguish all the limitations I have talked about. Also, I intend to study more clinical cases and analyse the causality test on more subjects and trials. With this work, I am pursuing to run into a Foundation to Science and Technology (FCT) scholarship and extend it to a Doctorate of Philosophy (PhD) study on computational neuroscience.

On the whole, acquiring EEG signals is still a challenging task and requires tricks to face some delicate steps, such as positioning the electrodes on the scalp or setting the more appropriate sampling frequency [49], however, with the advances in medicine and signal processing, it is expected to be able to possibly predict, earlier, more accurately epilepsy events and reinvent more ways of analysing the neuronal networks more precisely, with non-invasive approaches, intervening with more certainties on neurodegenerative diseases, such as Alzheimer's disease.

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