EEG Mapping Aural Stimulation

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Abstract

This study of musical neuroscience sought to map out and characterize the changes in electroencephalographic signals (EEG) experienced by 54 volunteers, both non-musicians (NM, 30) and musicians (M, 24), when submitted to aural stimuli (EA), with the aim of developing procedures useful for neuromodulation. We set out to verify whether those EA - monaural (EAM), binaural (EAB), simple, complex, or musical in nature - provoked changes in the emotional and cognitive states that could point to different auditory perceptions. Through the use of the EEG technique, it was possible to register, characterize and map out the changes in cerebral rhythms. Through the application of a percentual parameter named «variation in stimulus-antestimulus» (VEA), it was possible to statistically analyse the changes in the brainwaves caused by the EA. NM and M perceived the EA distinctly. It was observed how specific values both in the carrier frequency (FP) and the beat frequency (FB) of EAM and EAB distinctly influenced the EEG registered among the two groups, inducing different mental states. Complex EAB provoked different and complex patterns in the EEG. The human brain discriminates among different levels of musical complexity, distinguishing between non-musical and musical sounds. M was more reactive to the EA. NM applied a greater procedural cognitive investment in order to interpret the EA. Maps for the EA capable of provoking EEG changes in the scalp were created. These results are relevant for the improvement of cognitive performance, and may be useful in the treatment of neurological and psychiatric disorders.

Keywords: Neuroscience of Music, Electroencephalography, Aural Stimuli, Monaural Stimuli, Binaural Stimuli, Musical Perception

1. INTRODUCTION

For what reason do some sounds induce sleepiness, while others provoke a feeling of relaxation - while yet others seem to increase our concentration? What is music? Why do certain auditive sequences overwhelm us, while others make us uncomfortable? Why do specific songs make us emotional, and yet we feel so ambivalent towards many others, and even actively despise a few of them? What is the role of auditive and musical perception in this process? What are the distinctive traits that characterize musical perception among the groups of musicians (M) and non-musicians (NM)?

The difficulty of studying emotions and music in a scientific context stems from a deeply idiosyncratic and heterogeneous range of reactions and emotional responses, which depend on a complex variety - of particularly difficult control - of individual, sociocultural, historical, educational and familiar contexts [1]. This appears as an obstacle ahead of any examination of the cerebral changes provoked by musical stimul, and it explains the difficulty in implementing a consistent experimental protocol. One's appreciation and understanding of musical language is largely owed to education, to a cultural context, among an infinitude of other social factors. Thus the wide range of musical preferences we find in society - sometimes radically differing between individuals[2].

Through this study [3], we sought to answer some of the questions here put forward, and to better understand how music and sound affect our cognitive and emotional processing. The study of neurostimulation carried out in this project will contribute to a deeper understanding of cerebral stimulation through aural stimuli (EA). The scientific relevance of the research revolves around how, in enabling the characterization and the mapping of changes in electrocortical signals in different areas of the brain, it will allow for the elaboration of topographic maps of the scalp, where the responses will take place - allowing for their quantification, and subsequently for the establishment of neural patterns for the different EA. In this respect, the applications of the study could acquire a social dimension, namely in a clinical context (contributing to the potential development of procedures of neurostimulation, as a non-invasive technique for the treatment of neurological and psychiatric disorders), as well as contributing to improvements in our quality of life and in cognitive performance [4 - 9].

This study of musical neuroscience seeks to map out and characterize the changes in EEG signals experienced by M and NM volunteers, when submitted to EA. The aim is to verify whether those EA - monaural (EAM), binaural

(EAB), simple, complex, or musical in nature, with differing levels of structuring - provoke changes in the emotional and cognitive states that could point to different auditive and emotional perceptions. The application of the methodology will allow for the testing of the following hypotheses: 1) different and specific values of FP and FB in monaural and binaural sounds influence differently the EEG signals, inducing distinct mental states, 2) complex binaural sounds provoke distinct complex patterns in EEG monitoring, 3) the human brain discriminates between different levels of musical complexity, distinguishing non-musical from musical sounds, 4) the increase in musical structuring is directly related to an increase in cerebral activity, and 5) more complex cognitive processes are observed when exposed to vocal music, where the transmission of a verbal message is involved.

The effects of EAM and EAB have predominantly been researched using monaural and binaural beats (**Figure 1.1**). In this figure we can observe the overlay of the amplitude of the signals modulated with close frequencies, in a case where the hearing is happening in a single ear or in both simultaneously (monaural beats, frequencies or sounds), or in a case in which each of these close frequencies is separately distributed through each ear (binaural beats, frequencies or sounds). Pure tones or pure frequencies of 145 Hz and 155 Hz generate a beat frequency of 10 Hz (150 Hz is the central frequency, designated as carrier frequency).

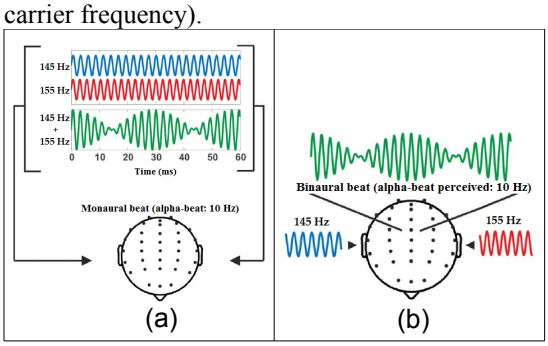

Figure 1.1 - (a) Application of monaural beats, frequencies and sounds and, (b) application of binaural beats, frequencies and sounds (source: adapted from [10, p. 4]).

The main differences between the monaural and binaural beats are listed in **TABLE 1.1**.

TABLE1.1 - Main differences between monaural and binaural.

Monaural beat	**Binaural beat**
Physical/ objective beat	Subjective percept
Presentation of composite frequencies to one ear or both ears simultaneously	Presentation of neighboring frequencies to each ear separately
Peripheral	Central
Demodulated in the coclea	Processed in the medial superior olivary nuclei
Able to be perceived in either one or both ears	Require combined action of both ears
Heard across a wider beat frequency range and a higher carrier tones	Present when beat frequencies are low and with carrier tones below 1000 Hz

The interest in the study of the influence of EA on the electrical activity of the cerebral cortex has increased in recent years, allowing for a deeper understanding of how the human brain receives, perceives and interprets EA [10, 15, 16, 18-21]. Music, as a complex sequence of EA, has not been an exception. As an affective-reflective language [11], which describes or evokes emotions, it has been studied as the activator or generator of physiological (so-called peripheral, which can be measured quantitatively, as in the case of the skin's conductivity, the cardiac rhythm, and the monitoring of EEG signals) and psychological responses for the subject who listens and perceives. Hence the high number of studies about emotions induced by music in EEG - which, on one hand, allow for the discovery of common (or, indeed, uncommon) patterns among groups of listeners, linking music with cerebral activity registered in the EEG; and, on the other, make possible the development of brain-computer interfaces (BCI, or Computer-Brain Interface, CBI). E. R. Miranda described in 2005 the potential development of an interface that enabled the direct connection between the brain and musical systems, which could subsequently create music through brainwaves [12]. Similarly, C. M. Fernandes describes a methodology for the sonification of the EEG acquired during sleep [13]. EAM and EAB have been amply studied for a wide range of applications. Binaural beat was first reported by H. W. Dove in 1839, and described by G. Oster [14] five decades later. The effects of the exposure to EAM and EAB on the memory, on the attention span, on anxiety and analgesia, have also been studied, as revealed in the meta-analytical study by M. Garcia-Argibay et al. (2018) [15]. The meta-regression seems to indicate that there is no need to mask the binaural beat with white or pink noise in order to achieve similar results, efficacy-wise, to the binaural beats without noise masking. Subjected to a task or cognitive test concurrent with the exposure to the binaural beats, the meta-analysis suggests that the exposure before the task, and during and after the task, yields superior results to the exposure during the task. The time of exposure contributed significantly to the model, suggesting that longer periods are advisable in order to ensure maximum efficacy. The study contributed to the growing evidence that exposure to binaural beats is an effective way of affecting cognition, decreasing anxiety levels and the perception of pain (without previous training), and that the magnitude of the effect depends on the frequency of the beat employed, the length of the exposure, and the moment in which it occurs. According to the literature review carried out by L. Chaieb et al (2015) [16], EAM and EAB could prove to be a new and promising tool in the manipulation of cognitive processes and the modulation of emotional states. Some studies suggest that EAM and EAB can be used to modulate cognition [17], decrease anxiety levels [18], and to induce certain emotional states [19]. Other clinical applications have proved their therapeutical efficacy in the treatment of cranioencephalic trauma [20] and ADHD (attention deficit hyperactivity disorder) [21]. However, some studies have presented seemingly contradictory results, suggesting that

EAM and EAB do not provoke significant effects either in cognitive processes or in emotional states [10]. The studies which have reported statistically significant effects state that EAB are frequently weak and of short duration, and that moreover there is little discussion over which mechanisms might be involved in the generation of those effects. This could be, at least partly, due to the nature of the EA themselves - that is, to the binaural beat being a weak perception, and to the fact that the majority of the studies did not deploy measuring techniques such as EEG in order to quantify the resulting electrophysiological effects. Another possible reason for the reported inconsistencies in the studies could be the incommensurable differences between methodological approaches.

2. MATERIALS AND METHODS

2.1. Volunteers

A total number of fifty four healthy volunteers (16 women and 38 men), aged between 22 and 70 (average ± sd for age: 36.3 ± 12.4 years), without any history of neurological and/or audiological disorders, took part in the study. The «non-musicians» group (NM) was made up by 30 volunteers (12 women and 18 men, average ± sd for age: 36.5 ± 14.6 years) and the «musicians» group (M) was made up by 24 volunteers (4 women and 20 men, average ± sd for age: 36.0 ± 9.4 years). Forty six volunteers were right-handed (DST), five were left-handed (CAN), and three of them had undefined laterality (LND). The inclusion criteria adopted were as follows: 1) volunteers aged 18 or over, 2) who had not had any pacemaker implanted, 3) who had not been diagnosed with epilepsy or schizophrenia, 4) who were not under the influence of any medication, alcohol or drugs, whether licit or illicit, 5) who were not afflicted by any other clinical condition that prevented the comprehension of and collaboration in the study, and 6) who were not pregnant. It was made available to every volunteer a document which aggregated the request for informed consent with a short survey. This document conveyed the aims of the study, general warnings, and offered a description of the experimental procedure. The volunteer's signature certified that he was aware and authorized, under the terms set forth in the General Data Protection Regulation (EU) n.º 2016/679, the necessary collection and processing of data (anonymized, and exclusively available to the research team). Every procedure was approved by the Ethical Committee of the Instituto Superior Técnico [22], and conducted according to the constant recommendations of the Declaration of Helsinki [23], the Declaration of Tokyo, and of the World Health Organization. The survey allowed for the placement of each volunteer in either group NM or M. Three questions were put forward to the volunteers: 1) whether they had any musical training, 2) whether they could play a musical instrument, and 3) whether they composed music. So as to be considered a musician, the volunteer would have had to reply positively to, at least, two questions, or simply to question 3). All other replies placed the volunteer in group NM.

2.2 Aural Stimuli

Three sequences of EA were created, SEQ1 (**TABLE 2.1**), SEQ2 (**TABLE 2.2**), SEQ3 (**TABLE 2.3, 2.4**), each one of them with 17 EA, totalling 51 EA. Each sequence had an approximate duration of 9 minutes. All of the EA were normalized at -6 dB, with a sample rate of 44 100 Hz, and a bit depth of 16 bit; during the collection of data, they were reproduced as wave files (*.wav), posing no risk to the volunteers' hearing. The monaural and binaural EA were produced with SBaGen (Sequenced Binaural Beat Generator) [24] and BrainWave Generator [25]. SoX (Sound eXchange) was employed to generate the spectrograms and Audacity allowed for the editing and digital normalizing of all EA, as well as their audio reproduction during the collection of EEG data.

TABLE 2.1 - List of EA in SEQ1.

EA	Type	Description of the EA/ Excerpt (10 seconds)
SEQ1-EA1	-	Pink Noise
SEQ1-EA2	-	Creek (fluvial environment)
SEQ1-EA3	Monaural	FP = 150 Hz [149 Hz + 151 Hz : L+R] FB = 2 Hz (delta)
SEQ1-EA4	Binaural	FP = 150 Hz [149 Hz (L) + 151 Hz (R)] FB = 2 Hz (delta)
SEQ1-EA5	Monaural	Pink Noise + FP = 150 Hz [149 Hz + 151 Hz : L+R] FB = 2 Hz (delta)
SEQ1-EA6	Binaural	Pink Noise + FP = 150 Hz [149 Hz (L) + 151 Hz (R)] FB = 2 Hz (delta)
SEQ1-EA7	Monaural	Creek + FP = 150 Hz [149 Hz + 151 Hz : L+R] FB = 2 Hz (delta)
SEQ1-EA8	Binaural	Creek + FP = 150 Hz [149 Hz (L) + 151 Hz (R)] FB = 2 Hz (delta)
SEQ1-EA9	Monaural	FP = 150 Hz [147 Hz + 153 Hz : L+R] FB = 6 Hz (theta)
SEQ1-EA10	Monaural	FP = 440 Hz (A4) [437Hz + 443Hz : L+R] FB = 6 Hz (theta)
SEQ1-EA11	Binaural	FP = 150 Hz [147 Hz (L) + 153 Hz (R)] FB = 6 Hz (theta)
SEQ1-EA12	Binaural	FP = 440 Hz (A4) [437Hz (L) + 443Hz (R)] FB = 6 Hz (theta)
SEQ1-EA13	Monaural	FP = 150 Hz [145 Hz + 155 Hz : L+R] FB = 10 Hz (alpha)
SEQ1-EA14	Binaural	FP = 150 Hz [145 Hz (L) + 155 Hz (R)] FB = 10 Hz (alpha)
SEQ1-EA15	Binaural	FP = 150 Hz [143 Hz (L) + 157 Hz (R)] FB = 14 Hz (low-beta)
SEQ1-EA16	Binaural	FP = 150 Hz [141 Hz (L) + 159 Hz (R)] FB = 18 Hz (beta)
SEQ1-EA17	Binaural	FP = 150 Hz [136 Hz (L) + 164 Hz (R)] FB = 28 Hz (high-beta)

Figure 2.1 - Brainwaves and frequency bands.

TABLE 2.2 - List of EA in SEQ2.

EA	Type	Description of the EA/ Excerpt (10 seconds)
SEQ2-EA1	Complex binaural	«Shaman dream» *Border meditation & sleep*
SEQ2-EA2	Complex binaural	«Mind awake & body asleep» *Trance meditation*
SEQ2-EA3	Complex binaural	«Learning aid (for subliminal)»
SEQ2-EA4	Complex binaural	«Mind power»
SEQ2-EA5	Complex binaural	«Concentration»
SEQ2-EA6	Complex binaural	«Focus»
SEQ2-EA7	Complex binaural	«Calm» Pink Noise + Delta 1.5 Hz + Theta 6 Hz FP1 = 100 Hz + FP2 = 150 Hz
SEQ2-EA8	Complex binaural	«Studying aid» *To concentrate and think clearly*
SEQ2-EA9	Complex binaural	«Learning aid (for studying)» *Learn & memorize*
SEQ2-EA10	Complex binaural	«Quick mental refresher (end relaxed)»
SEQ2-EA11	Complex binaural	«Deep chillout»
SEQ2-EA12	Complex binaural	«Self-hypnosis (complex)»
SEQ2-EA13	Complex binaural	«Self-hypnosis (simple repeating sound)»
SEQ2-EA14	Complex binaural	«Modulations»
SEQ2-EA15	Complex binaural	«12 Hz modulation»
SEQ2-EA16	Complex binaural	«Drop sequence»
SEQ2-EA17	Complex binaural	«Epileptic»

TABLE 2.3 - List of EA in SEQ3.

EA	Type	Description of the EA/ Excerpt (10 seconds)
SEQ3-EA1	EANM	Pink Noise
SEQ3-EA2	EANM	By the seaside, on the beach (Maritime environment)
SEQ3-EA3	EANM	Crying baby (Warning/beware)
SEQ3-EA4	EANM	Swarm of bees (Warning/danger)
SEQ3-EA5	EANM	Wind and creaking door (Scary environment)
SEQ3-EA6	EMPE	Hip Hop Rhythm (Rhythm)
SEQ3-EA7	EMPE	House Rhythm (Rhythm/Dance)
SEQ3-EA8	EMPE	«Mantra» Pad (Relaxing Sound)
SEQ3-EA9	EMPE	«Relaxation» Pad (Relaxing Sound)
SEQ3-EA10	EME	*Manitoba* *«Start Breaking My Heart»* (Electronic Music)
SEQ3-EA11	EME	*Anouar Brahem Trio* *«Astrakan Cafe»* (Arabic Music)
SEQ3-EA12	EME	*Barney Wilen* *«La Vie N'Est Qu'Une Lutte»* (Jazz Music)
SEQ3-EA13	EME	*Johannes Brahms* *«Hungarian Dance» N.º17 Andantino Vivace* (Classical Music)
SEQ3-EA14	EMEV	*Caballeros del Nuevo Milenio* *«Anima Christi»* (Gregorian Chant)
SEQ3-EA15	EMEV	Ana Laíns «O Fado Que Me Traga» (Sung Fado)
SEQ3-EA16	EMEV	Boss AC «Mantém-te Firme» (Sung Hip Hop)
SEQ3-EA17	EMEV	*Montserrat Caballé* *«In Quelle Trine Morbide»* *(Manout Lescaut)* (Opera)

TABLE 2.4 - Categorization of EA in SEQ3.

Categorization	Acronym	EA Classification
Non-musical Aural Stimulum	EANM	EA lacking any rhythm, harmony or melody. Ambient sound, non-musical.
Poorly Structured Musical Stimulum	EMPE	EA with a simple rhythmic, harmonic, or melodic structure.
Structured Musical Stimulum	EME	EA with rhythmic, harmonic, or melodic structure.
Structured Musical Stimulum with Vocals	EMEV	EA with rhythmic, harmonic, or melodic structure, and human voice.

2.4 Equipment and Signal Acquisition

The collection of data took place at the Instituto de Sistemas e Robótica's Laboratório de Sistemas Evolutivos e Engenharia Biomédica (LaSEEB-ISR, Instituto Superior Técnico), with an approximate duration of an hour and a half: around 45 minutes for the placement of the cap (Electro-Cap International Inc., Ohio, U.S.A., with 21 electrodes) and for setting up the EEG monitoring equipment; and another 45 minutes for the monitoring itself, while the volunteer listens to the 3 sequences of EA, with an interval of approximately 2-3 minutes between each sequence. The EEG signals were recorded using the 10-20 International System of Electrode Placement (Fp1, Fp2, F3, F4, F7, F8, C3, C4, T3, T4, P3, P4, T5, T6, O1, O2, Fz, Cz, e Pz), with a sample rate of 250 Hz. The earth electrode was placed in the middle of the forehead (through the cap's appropriate channel) and the reference used was the average of the signals captured through 2 gold-plated electrodes (channels A1 and A2), placed on the left and right mastoids (so as to improve the rejection of common-mode signals). The signals were amplified through an EEG Vertex 823 amplifier[1] with cerebral mapping (digital EEG machine SC 823 of 23 channels, AD resolution 16 bits, 1 024 samples/second per channel, incorporated electronic calibration, communication with PC TCP/IP(UDP) and USB 2; produced by Meditron Electromedicina Ltda, São Paulo, Brasil), and recorded through the Somnium software (Cognitron, São Paulo, Brazil). Before commencing each EEG monitoring session, the impedance of the circuit was, for every channel (impedance of the electrode-scalp contact), kept under 10 kΩ. The EEG data was individually collected from every volunteer, one at a time, in a quiet environment, with a comfortable room temperature, humidity and light, employing supra-aural headphones (Sony MDR-V55, frequency response 5 Hz - 25 000 Hz) (**Figure 2.2**). It was asked of each volunteer to sit comfortably, remaining inactive (without moving, until informed that the session was over; volunteers were requested to avoid ocular movement, even with their eyes closed, as well as any other movement, whether of fingers, hands, legs, tongue, etc). Once volunteer's eyes were closed, the EEG recording on Somnium (on PC1, with the soundcard installed) was initiated, while the reproduction of the EA sequences simultaneously began, using the Audacity software (on PC2, also with the soundcard installed). A 2 meter 3.5 mm jack stereo audio cable was connected to PC2's soundcard line-out, which was then connected to the line-in on PC1's soundcard. The headphones were connected to PC1's line-out. This configuration allowed for the recording of the EA sequences on one of

1 ANVISA-certified for clinical use (certifying entity for clinical equipment).

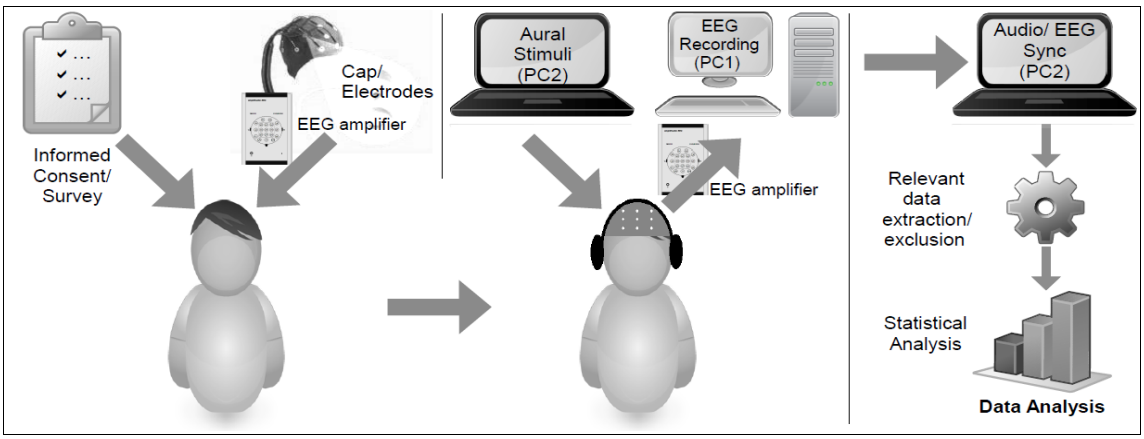

Figure 2.2 - Experimental protocol.

Somnium's audio channels (with a sample rate of 4 kHz, mono[2]), while simultaneously monitoring and recording 19 EEG signals.

2.5 Average percentage variation of Stimulus-Antestimulus (VEA)

The relative power of brainwaves could have been deployed; however, so as to mitigate potential interferences in the results (owing to the different situational states of each volunteer - their mood, nervousness, anxiety, consumption of coffee, among a plethora of possibilities), the use of absolute power was favored. With this in mind, a parameter was created which could account for and lessen the impact of those states, the (average) percentage variation of stimulus-antestimulus (VEA),

$$\overline{VEA}_j = \frac{\overline{P(E_j)} - \overline{P(AE_j)}}{\overline{P(AE_j)}} x100 \, , j = 1,...17 \quad (1)$$

in which $\overline{P(E_j)}$ is the (average - during 10 seconds, the fixed duration for each of the 51 EA) absolute power (stated in μV2/Hz) of EA j and $\overline{P(AE_j)}$ is the (average - during 5 seconds, immediately before the EA) absolute power of the antestimulus j. The VEA parameter thus translates the change in the volunteer's emotional and cognitive state when exposed to the EA, with particular interest in the measurement of the state provoked by the EA against that which precedes the EA.

2.6 Preprocessing and Data Extraction

In Somnium, and after the collection of the EEG signals, the .spj files were exported to .edf[3], EDF format (European Data Format) [26]. The preprocessing, the extraction and the treatment of data, the graphs, the topographic maps of the scalp and the statistical analysis were carried out using the MatLab software (version R2015a, MathWorks, Natick, USA), and the FieldTrip toolbox [27], with various scripts created for the various steps in this analysis. Through the information in the temporal sequence of the EA in SEQ1, SEQ2 and SEQ3 (duration of the silences, of the EA, of the antestimuli and of the audio tags[4]), it was possible to detect, select and define, in the audio channel registered simultaneously with the EEG signals, the relevant trials of the EEG signals in the 19 channels, corresponding to the 51 antestimuli and the 51 EA.

2.7 Data Treatment

It was possible to determine, for every volunteer, the absolute power[5] of each trial (power per trial) corresponding to the antestimulus and the EA, according to fast Fourier transform (FFT) of the segmented data and for the relevant frequencies defined by option of configuration cfg.foi = 0.5:0.5:30 (between 0.5 Hz and 30 Hz, every 0.5 Hz). It was possible to simultaneously visualize the topographic maps of the scalp for the six frequency bands (**Figure 2.1**) considered in the study (delta, theta, alpha, low beta, beta and high beta) for each volunteer and for every antestimulum/ EA (**Figure 2.3**).

2.8 Exclusion and Normality of Data

The detection of artifacts during the recording of signals was also a valid and decisive reason to exclude data. These artifacts have their origin in electric potentials generated by sources other than the one measured in the scalp [28]. With this in mind, a number of normality tests were applied to the collected data for the groups of volunteers NM and M, with the purpose of determining the value of VEA beyond which data would be excluded, so as to maximize the normality of data (great number of results for H = 0, coinciding with the failure to reject the null hypothesis H0, on which VEA follows a normal distribution DN). It is therefore accepted that the excluded data results from artifacts in the EEG. The test which showed better results was the Lilliefors, for a data exclusion |VEA| > 90%.

2 The decision underlying this choice of sample rate, along with the option for monophony, has two main justifications: 1) so that the resulting Somnium files would not take up an excessive amount of space per volunteer, and 2) so as not to impair the software's performance during the collection (and real-time visualization) of data.

3 The name of each volunteer's EDF file was encoded (for instance, ABCD_1234.edf).

4 Pure frequency of 20 Hz, with the duration of 2 seconds, beginning 5 seconds before each EA.

5 PSD, Power Spectral Density, in μV2/Hz.

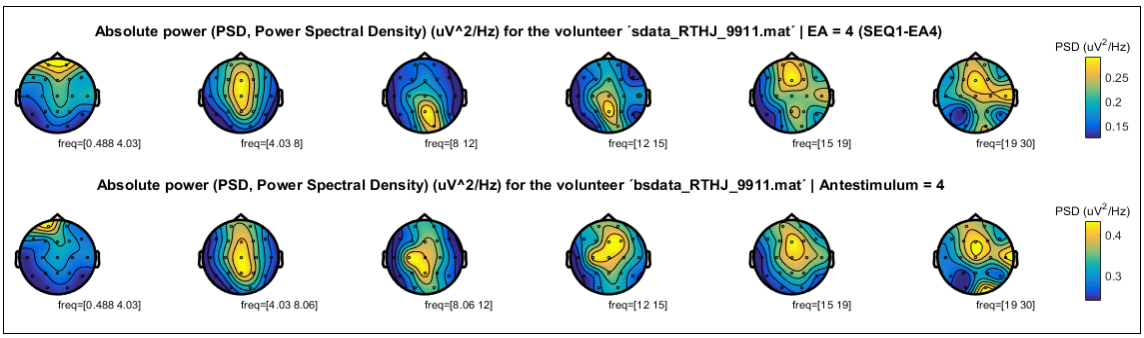

Figure 2.3 - Topographic maps of the scalp for the absolute powers in the EA/antestimulus = 4, for the 6 brainwaves under investigation, for the volunteer RTHJ_9911.

2.9 Statistical Analysis

Using the Lilliefors normality test (with a null hypothesis H0, which establishes that, for each trial, the VEA average follows a normal distribution, in which if H = 1 the test rejects H0 for α = 5%, otherwise H = 0), and the condition for data exclusion[6] |VEA| > 90%, it followed that, for group NM, 58% of data followed a normal distribution and 42% did not; whereas for group M, 65% of data followed a normal distribution while 35% did not. To study significant differences between groups of subjects or parameters, non-parametric and parametric tests were used ($p < 0.05$).

3. RESULTS AND DISCUSSION

3.1 Total VEA average for all of the channels, regarding EA in SEQ1, NM and M groups

The exploratory analysis of the total VEA average was carried out, for all of the channels, regarding the EA in SEQ1, covering both NM and M groups, for: i) all brainwaves (**Figure 3.1**), ii) delta brainwaves, iii) theta, iv) alpha, and v) beta. It becomes clear that the total VEA average is always negative, increasing and decreasing through the sequence of EA. According to the definition of the VEA parameter, we can establish that in the silence of the antestimulus the power of the EEG signal is greater than the power obtained during the stimulus - there is, therefore, a suppression of the signal, that is, a decrease in the amplitude of EEG signals. Some studies [29, 30] suggest that this suppression is linked with the activation of cerebral areas associated with cognitive processing. The VEA[7] establish readings for groups NM and M are distinct and demonstrate trends that are worth emphasising. VEA in the first EA is more negative in group M than in group NM, evidencing a greater change and a bigger suppression in EEG signals. The results obtained show that EAM and EAB reveal their effectiveness in provoking significant EEG changes - which does not erase the differences these variations present between groups NM and M. We can ascertain that for FB < 6 Hz (theta), the transition (with and without the pink noise and the creek sounds) from monaural EA to binaural EA does not lead to a significant change in EEG. This is not the case for FB > 6 Hz, where the VEA, in general, becomes more negative, indicating the activation of cortical areas dedicated to cognitive processing. The inclusion of the pink noise and the creek sounds in the

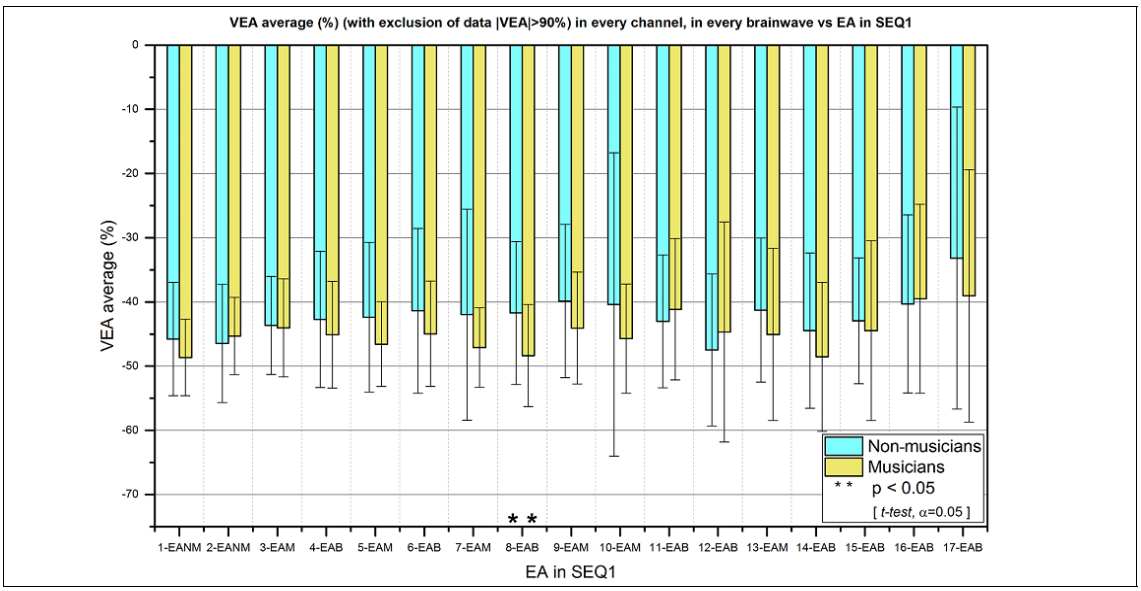

Figure 3.1 - Graphic representation of the total VEA average for every brainwave, for SEQ1 of EA, for the NM and M groups.

6 The exclusion of data corresponds, from a computational standpoint, to the replacement of numerical values with NaN (Not a Number).

7 The error bars correspond to the standard deviation of the VEA average, $\pm \Delta VEA = \pm sd(VEA)$.

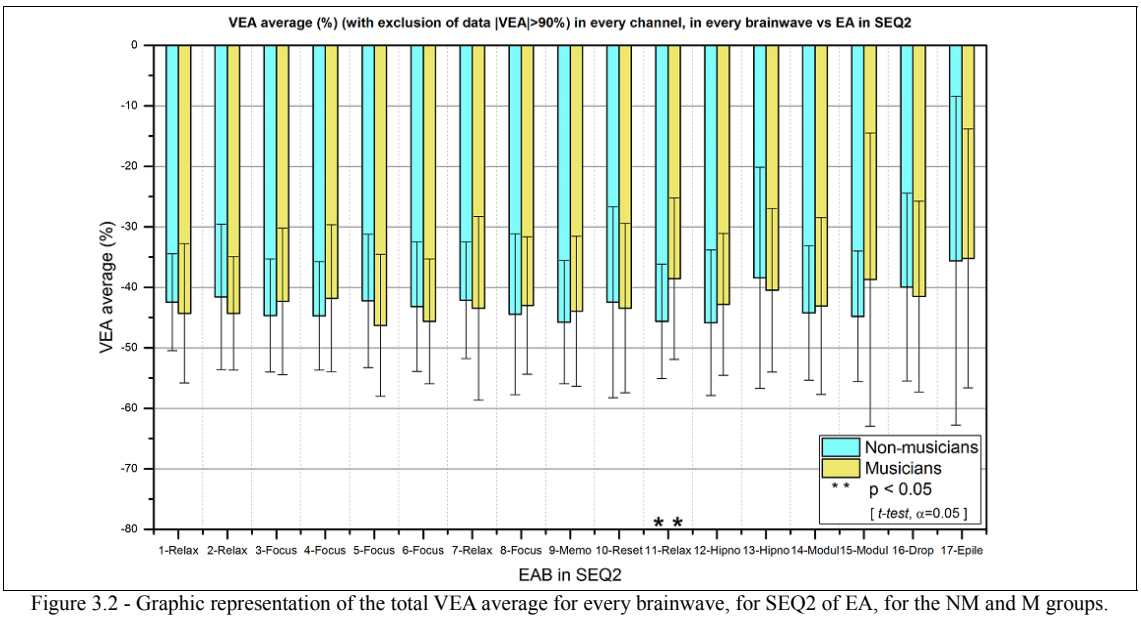

Figure 3.2 - Graphic representation of the total VEA average for every brainwave, for SEQ2 of EA, for the NM and M groups.

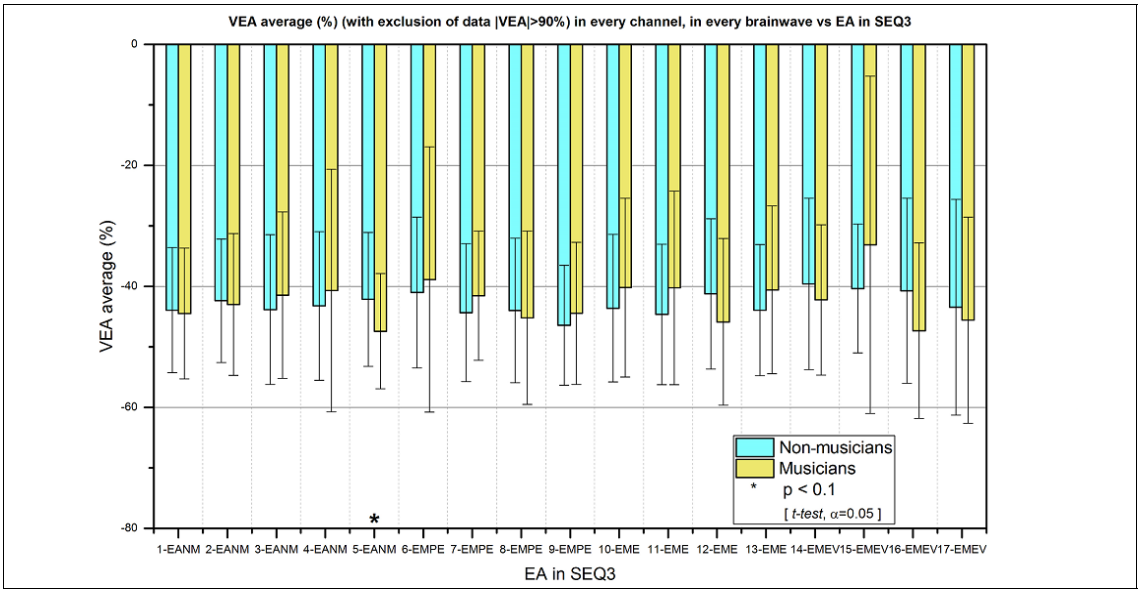

Figure 3.3 - Graphic representation of the total VEA average for every brainwave, for SEQ3 of EA, for the NM and M groups.

monaural EA made the VEA, in general, increasingly negative - the creek sounds were particularly effective in this respect. The increase in FP, too, from 150 Hz to 440 Hz (both for monaural and binaural EA), made the VEA additionally negative. Contrasting the results obtained from groups NM and M, we reach the conclusion that auditory perception was fundamentally distinct, with group M demonstrating a greater reactivity to the EA than group NM.

3.2 Total VEA average for all of the channels, regarding EA in SEQ2, NM and M groups

The exploratory analysis of the total VEA average was carried out, for all of the channels, regarding the EA in SEQ2, for: i) all brainwaves (**Figure 3.2**), ii) delta brainwaves, iii) theta, iv) alpha, and v) beta. In similarity with the observations for SEQ1, for all of the channels and all of the brainwaves, we established that the total VEA average is always negative, increasing and decreasing throughout the EA sequence. The VEA readings for groups NM and M are distinct, and demonstrate trends that are worth emphasising. The VEA in the first EA is more negative in group M than in group NM, evidencing a more intense change and a greater suppression of EEG signals. Comparing the total VEA average between NM and M groups, for all the channels and all the brainwaves, three occurrences were established coinciding with EA transitions in group NM (in which the variations in mental states take place, as suggested by the presets created by the software which generated the EA: relaxation → focus, mental reset → relaxation and hypnosis → modulations), where the VEA becomes more negative; in group M, two transitions were observed where the VEA also becomes more negative (focus → focus and relaxation → hypnosis). Considering these results, we note how the group NM, in this SEQ2 of EA, was more reactive than group M. The increase in the intensity of EEG changes in group NM, in the

aforementioned transitions, along with a greater suppression of EEG signals, suggesting the activation of cortical areas responsible for cognitive processing, may be explained by the necessity of a greater cognitive effort in order to understand the EA (although these were, like in SEQ1, non-musical, EANM); group M would, by implication, «understand» the EA in a quicker and more direct way. Mirroring what we had observed in SEQ1, we must suggest a distinct cognition between groups NM and M when exposed to complex EAB, such as the ones created for SEQ2.

3.3 Total VEA average for all of the channels, regarding EA in SEQ3, NM and M groups

The exploratory analysis of the total VEA average was carried out, for all of the channels, regarding the EA in SEQ3, covering both NM and M groups, for: i) all brainwaves (**Figure 3.3**), ii) delta brainwaves, iii) theta, iv) alpha, and v) beta. In similarity with the observations for SEQ1 and SEQ2, for all of the channels and all of the brainwaves, we established that the total VEA average is always negative, increasing and decreasing throughout the EA sequence. The VEA readings for groups NM and M are distinct, presenting some significant contrasts that are worth emphasising. For the first EA, the VEA has approximately the same value in groups NM and M. From EA = SEQ3-EA6 onwards, coinciding with the change in aural categorization from EANM to EMPE, where the transition from non-musical to musical stimulus occurs, the VEA tends to become more negative. In the transition EA = SEQ3-EA9 → EA = SEQ3-EA10, corresponding to the categorical change from EMPE→EME (in which the complexity of the musical structures increases), we note how, for both groups, the VEA tends to become less negative. Group NM, we might suggest, employs a greater effort in cognitive processing so as to interpret the EA; in contrast, group M possesses the tools of music language and expression, which spares its members from employing complex cognitive and memory operations. While keeping in mind the strong idiosyncratic and heterogeneous EEG responses from the volunteers (which depend on a complex variety - of difficult control - of individual, sociocultural, historical, educational and familiar contexts), we must nevertheless acknowledge that an increase in the complexity of the EA - namely in the transition from non-musical to musical - provokes changes in the VEA. In certain circumstances, it makes its value additionally negative, hinting at significant changes in cognitive and emotional states, a tendency that is heightened in the presence of more complex EA - namely, those of a musical nature with the presence of human voice. These results validate the initial auditory categorization of the EA.

3.4 Topographic maps of VEA in the scalp, for groups NM and M

The topographic maps of the scalp for the total VEA average, regarding EA in SEQ1, SEQ2 (example in **Figure 3.4**) and SEQ3, for groups NM and M, and for the various cerebral rhythms.

3.5 Maps of EA generative of EEG changes in the scalp, for groups NM and M

Owing to the topographic maps of the scalp for the VEA parameter, and for the various cerebral rhythms, regarding EA in SEQ1, SEQ2 and SEQ3, for groups NM and M, it was possible to create maps of EA generative of more intense EEG changes (that is, when the maximum values of the VEA module are reached). This was achieved through a graphic representation that enables us to learn which EA provokes a greater EEG variation in a certain cortical area (EEG channel), for a specific brainwave (for SEQ1, in group NM, see **Figure 3.5**).

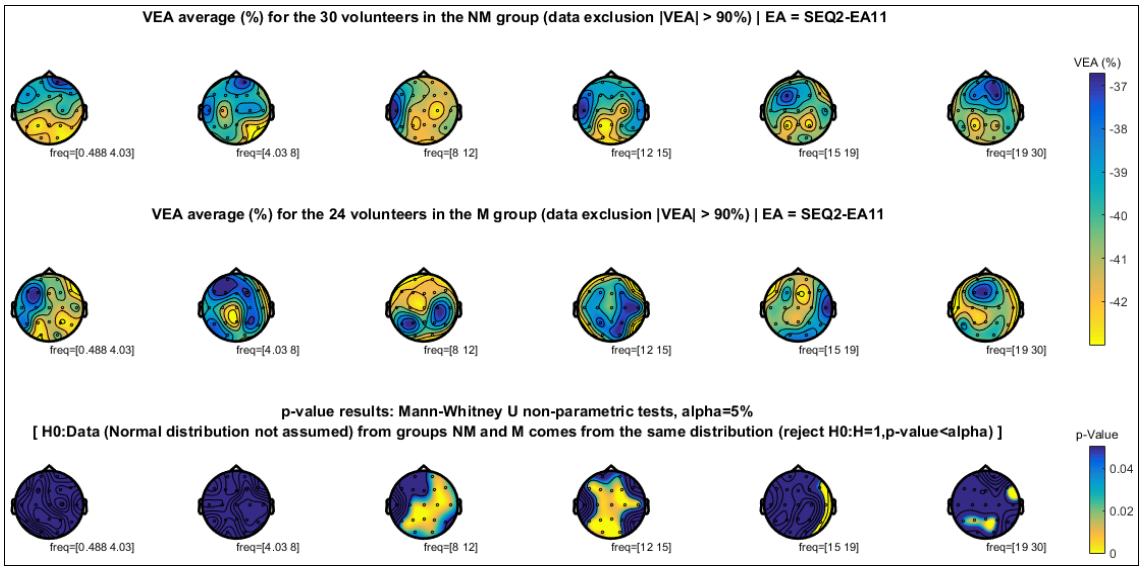

Figure 3.4 - Topographic maps of the scalp for the VEA in EA=SEQ2-EA11 and p-values results, in groups NM and M.

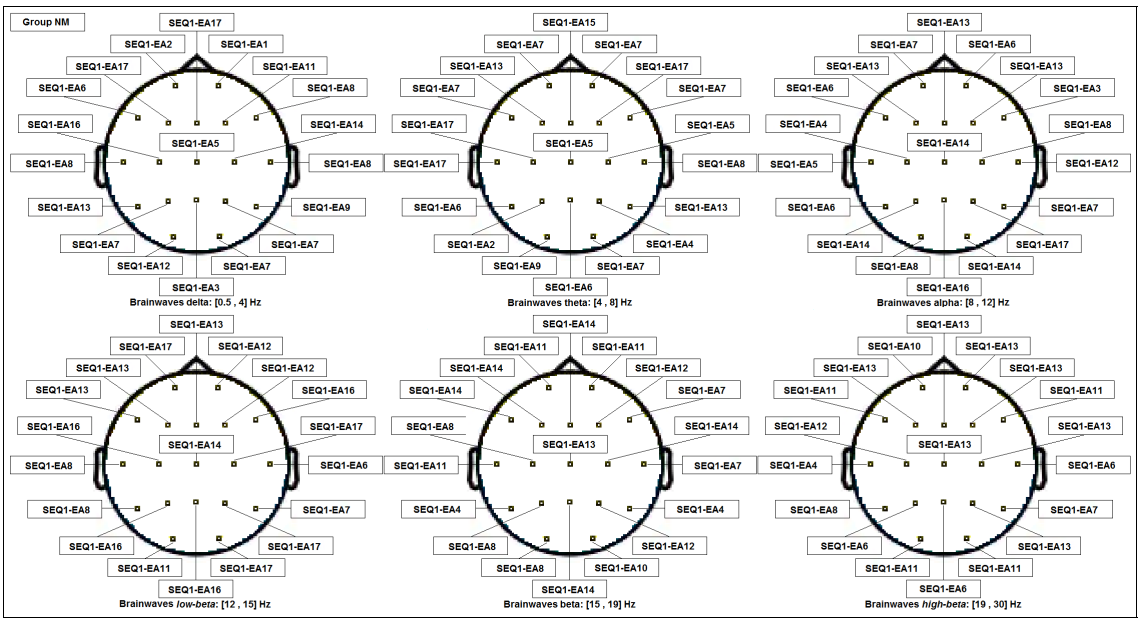

Figure 3.5 - Maps of EA-SEQ1 generative of EEG changes in the scalp (group NM).

4. CONCLUSIONS AND FUTURE RESEARCH

The VEA has shown itself to be a reliable parameter for data treatment, effectively suppressing the volunteers' situational factors - such as their mood, nervousness, anxiety, coffee consumption, among others. Departing from a base reference of the scalp for each EA and for every volunteer, the VEA has allowed us to measure the intensity of EEG changes - of that which is activated in the cerebral cortex when the EA are heard. The total VEA average was always negative, increasing and decreasing through the sequences of EA SEQ1, SEQ2, SEQ3. The VEA readings for groups NM and M were distinct and showed different trends. It is concluded that the human brain discriminates among different levels of musical complexity, distinguishing between musical and non-musical sounds. In the EA coinciding with the change in auditory categorization from EANM→EMPE, the VEA tended to become more negative. In the change in categorization from EMPE→EME (in which the complexity of the musical structures increased), it was observed how, for both groups, the VEA tended to become less negative. In group M, VEA was less negative than in group NM - which seemed to occur, on average, throughout the entire sequence of EA, with occasional exceptions. It is suggested that group NM required an additional effort in cognitive processing so as to interpret the EA; in contrast, group M, owing to its grasp of the musical language and expression, seemed not to rely on complex cognitive and memory operations. The increase in the complexity of EA, namely in the transition to musical EA, induced variations in the VEA and, in some cases, made its value more negative, hinting at the presence of important changes in the cognitive and emotional states, which was heightened by the more complex EA - those musically structured, and where human voice was present. These results justified the initial auditory categorization of EA.

It was possible to create maps of EA generative of more significant EEG changes (which occurred when the maximum values of the VEA module were reached); this graphic representation enables us to learn which EA provokes a greater EEG variation in a certain cortical area, for a given brainwave, for groups NM and M. These EA maps will potentially be applied in the development of procedures useful for neuromodulation, as a non-invasive technique; as some studies suggest, they may equally prove fruitful in the clinical field, in the treatment of neurological and psychiatric disorders, as well as in the enhancement of cognitive performance. This prospective study accounted for multiple parameters. The study allowed us to reach the aims we originally set out to achieve, paving the way for future research. There were, however, certain aspects which placed constraints on the statistical power of the study, for example, the sample size of the groups NM and M. In light of these limitations, it will be interesting to increase the number of participants in future studies, so as to deepen our understanding of issues related to cognitive behaviour and performance. Another relevant conclusion lies with the duration of the EA. Practically every study involving monaural and binaural EA [15] employed EA lasting for several minutes - in stark contrast with the (short) duration of 10 seconds implemented in this study. The option for this duration is indebted to the results obtained by H. Moreira (2011) [29] in the preliminary study that proved the efficacy of this duration, allowing for a better resolution in the electrocortical response to the EA. It ensures that the response is mostly owed to the EA, rather than to other eventual mental mechanisms, such as the imagination or cognitive processes involving the memory. In addition to this, this model, being quicker, is also more comfortable for the volunteer.

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