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Influence of beta and theta binaural beat stimulation on episodic memory: an EEG study

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Abstract

Binaural beats (BBs) are auditory illusions created by the brain when two coherent sounds with slightly different frequencies are presented to both ears dichotically. For example, if the subject is presented a 256 Hz tone to the right ear and a 250 Hz to the left ear, the beat in this phenomenon is referred to as a 6 Hz theta binaural beat. Conversely, a mix of two sinusoids presented to the same ear is called acoustic beat (AB), resulting in a periodic amplitude fluctuation. Although BBs were shown to have positive effects on cognition, there are no sufficient studies on BBs and episodic memory. Furthermore, there is no agreement to explain the brain mechanism underlying the perception of BBs. The primary goal of this study is to investigate the influence of BBs on episodic memory and the effects of BB stimulation on brain rhythms, more concretely to examine whether they can change the power of specific EEG frequencies, comparatively to ABs. The secondary objective focuses on an exploratory study to measure cortical auditory evoked potentials (CAEPs) applying Muse, a consumer-grade EEG device used in this study, in order to assess its potential and the corresponding data quality. To meet the goals, two separate experiments were designed: a classic CAEP paradigm, with a total of 5 participants (3 male, 2 female; aged 22-25 years old); and an experiment with 32 subjects (19 male, 13 female; aged 20-28 years old), divided into two groups (depending on type of stimulation performed: 20 Hz beta or 6 Hz theta beats), each one with two stimuli conditions (BB or AB), received 15 minutes before the episodic memory task, during memory encoding phase and during the free recall test, across 2 sessions with an interval of 1 week. To quantify the power of brain oscillations during AB and BB stimulation, time-frequency analysis was performed using Discrete Wavelet Transform (DWT) and Relative Wavelet Energy (RWE). Regarding CAEP paradigm, N1-P2 complex was detected in temporal regions with acceptable signal-to-noise ratio. Parametric and non-parametric paired t-tests showed several significant changes in RWE values within each group at different time points, frequency bands and channels during both sessions, between BB and AB conditions. Moreover, entrainment of brain activity with the frequency of the beat was detected within theta BB stimulation. Regarding the effects of BB stimulation on episodic memory performance, t-tests revealed significant differences in the memory scores between AB and BB conditions during the first session ($t=-2.48$, $p=0.0133$) and second session ($t=-2.67$, $p=0.00914$) in theta group, with higher scores observed after BB stimulation. In beta group, significant differences in the scores were observed between AB and BB conditions during first session ($t=-2.40$, $p=0.0154$), with higher scores registered in BB condition. Inter-group analysis demonstrated that beta group outperformed theta group in both AB ($t=3.37$, $p=0.00244$) and BB ($t=3.58$, $p=0.00143$) conditions during the second session. This study validates the use of Muse for neuroscientific research, demonstrating that is possible to rely on consumer-grade low-cost EEG systems. Furthermore, it demonstrates that 20 Hz beta and 6 Hz theta BBs have a positive influence on episodic memory performance. Based on findings of positive effects of BBs on cognition, these results were expected. Entrainment was observed during theta BB stimulation. In addition, it is suggested that BBs have a modulatory effect on brain frequencies, with involvement of dynamical processes.

Keywords: binaural beats, episodic memory, wavelet analysis, cortical auditory evoked potentials, Muse, EEG

Resumo

Batimentos binaurais (BBs, do inglês *Binaural beats*) são ilusões auditivas criadas pelo cérebro quando dois sons coerentes com frequências ligeiramente diferentes são apresentados dicoticamente, isto é, cada ouvido é estimulado por frequências diferentes. Existem diferentes tipos de BBs, dependendo das frequências a partir das quais são criados e da diferença entre elas, o que determina a frequência do batimento. Por exemplo, se o sujeito é apresentado com um tom de 256 Hz no ouvido direito e 250 Hz no ouvido esquerdo, cria-se um batimento binaural de 6 Hz, na frequência do ritmo teta. Por outro lado, a mistura de duas sinusoides apresentadas ao mesmo ouvido possui o nome de batimento acústico (AB, do inglês *acoustic beat*) e as suas interferências são refletidas em flutuações periódicas em amplitude.

Estudos demonstram que os BBs têm um efeito positivo na memória de trabalho, memória de longo prazo, capacidade de atenção e nos níveis de ansiedade e relaxamento. No entanto, existem relatos do seu efeito negativo na atenção e na memória de curto prazo. Para além disso, não existe um consenso na comunidade científica para explicar o mecanismo cerebral subjacente à perceção dos BBs. Tudo isto sublinha a necessidade de mais unificação na pesquisa.

Apesar do efeito benéfico dos BBs nos diferentes tipos de memória, não existe um leque de estudos suficientemente grande relativamente à sua influência na memória episódica, um tipo de memória associado à codificação de eventos autobiográficos. Destaques na pesquisa sugerem que as oscilações teta estão associadas a um melhor desempenho na memória episódica. Presumindo que a estimulação auditiva com BBs teta possa ter um efeito modulador das frequências cerebrais por meio de resposta pós-frequência, mais especificamente no ritmo teta, é razoável supor que os BBs podem influenciar a memória episódica.

O sistema de EEG usado neste estudo é o *Muse*, desenvolvido para ajudar em técnicas de meditação. Como não se trata de um aparelho de grau médico, é necessário entender se o material é viável para o estudo. O método para alcançar esta validação foi medir os potenciais evocados auditivos corticais, uma resposta cerebral já bem conhecida. Posto isto, a primeira parte desta tese foca-se num estudo exploratório para medir os potenciais evocados auditivos corticais usando o *Muse*, com o objetivo de avaliar o potencial do dispositivo e a qualidade dos dados correspondentes. A segunda parte e a meta principal deste estudo é investigar a influência do BBs na memória episódica e estudar o seu efeito nas oscilações cerebrais, em comparação com ABs.

Para concretizar a primeira experiência deste estudo, um paradigma clássico foi desenhado para medir os potenciais evocados. Um total de 5 voluntários participaram neste estudo, com idades compreendidas entre 22 e 25 anos. Os participantes receberam um total de 180 estímulos, que consistiam em tons puros de 1000 Hz, com 500 ms de *plateau*, 10 ms de subida e descida e apresentados a cada 2 segundos. A aquisição do EEG e os marcadores de evento foram concretizados através do *Lab Streaming Layer*, uma ferramenta que permite criar redes de conexões entre vários dispositivos e programas. O pré-processamento e o processamento dos dados foram executados no EEGLAB, uma extensão do MATLAB que oferece uma interface gráfica para realizar a análise do EEG. Os resultados obtidos foram satisfatórios: o complexo N1-P2 foi identificado em todos os sujeitos e também nas curvas de grande média, com uma melhor relação entre o sinal e o ruído comparativamente às curvas individuais.

Relativamente à segunda parte desta tese, a experiência consiste em 2 grupos de sujeitos, 2 blocos de tarefas, cada um com 2 condições de estímulo (AB ou BB), concretizada durante 2 sessões, separadas por uma semana. Um total de 32 voluntários foram recrutados, com idades compreendidas entre 20 e 28 anos. Os sujeitos foram divididos em 2 grupos: grupo teta, que recebeu estimulação com BBs e ABs

teta na frequência dos 6 Hz, criados a partir de tons puros de 247 Hz e 253 Hz; grupo beta, que foi estimulado com BBs e ABs beta na frequência dos 20 Hz, gerados a partir de tons puros de 240 Hz e 260 Hz. A primeira parte do primeiro bloco consistia numa tarefa passiva em que os sujeitos de cada grupo ouviam ABs durante 15 minutos, ao mesmo tempo em que aquisição do EEG era realizada. Seguiu-se uma tarefa de memória episódica, em que os participantes tinham que decorar uma sequência de 30 imagens de objetos, cada uma com a duração de 3 segundos. De seguida, uma tarefa de distração foi realizada consistindo numa contagem em voz alta de 20 até 0. Por fim, foi feito um teste de recordação livre em que os sujeitos apontavam num papel os objetos que se lembravam de ver, cujo número seria contabilizado como pontuações de memória. O segundo bloco de tarefas é idêntico ao primeiro, exceto que imagens de objetos diferentes foram usadas e a estimulação durante os 15 minutos iniciais foi feita com BBs. Na segunda sessão, os mesmos procedimentos foram repetidos, exceto o uso de imagens de objetos diferentes em cada bloco.

Para quantificar a energia de cada banda de frequência do EEG, recorreu-se à Transformada de Wavelet Discreta, que decompõe o sinal em vários níveis, cada um correspondendo a uma banda de frequência de ritmos cerebrais, e à Energia de Wavelet Relativa (RWE, de *Relative Wavelet Energy*). Mudanças na RWE dum determinado nível de decomposição refletem mudanças na atividade cerebral na banda de frequências correspondente. Dois tipos de análise foram concretizados: um tendo conta a evolução temporal da RWE ao longo de 13 segmentos de 1 minuto; o segundo implicou calcular a RWE média ao longo de um único segmento de EEG, colapsando a dimensão temporal. Os testes *t* paramétricos e não paramétricos revelaram várias diferenças entre os valores de RWE durante a estimulação com ABs e a estimulação com BBs, ao longo de diferentes instantes de tempo, bandas de frequências, canais e sessões da experiência. Relativamente ao grupo teta, os testes revelaram que a RWE na banda de frequência alfa no canal AF8 durante a primeira sessão aumentou de AB para BB ($t=2.2701$, $p=0.01919$). Durante a segunda sessão, foi observado um aumento dos valores de RWE na banda de frequências teta no canal TP10 da condição AB para BB ($t=2.4509$, $p=0.0135$). Relativamente ao grupo beta, as seguintes observações correspondem à primeira sessão, da condição AB para BB: uma diminuição significativa de RWE na banda de frequências beta no canal TP10 ($t=-2.3364$, $p=0.0181$) e um aumento significativo de RWE na banda delta no canal TP10 ($t=4.3193$, $p=0.0004164$) e no canal TP9 ($t=2.7144$, $p=0.00885$).

Quanto aos efeitos dos BBs na performance de memória episódica, os testes *t* revelaram diferenças significativas nas pontuações entre as condições AB e BB durante a primeira sessão ($t=-2.48$, $p=0.0133$) e segunda sessão ($t=-2.67$, $p=0.00914$) no grupo teta, com pontuações mais altas observadas após a estimulação com BB. No grupo beta, diferenças significativas nas pontuações foram observadas entre as condições AB e BB durante a primeira sessão ($t=-2.40$, $p=0.0154$), com pontuações mais elevadas registadoa na condição BB. A análise entre os grupos demonstrou que o grupo beta superou o grupo teta em ambas as condições AB ($t=3.37$, $p=0.00244$) e BB ($t=3.58$, $p=0.00143$) durante a segunda sessão. Uma análise fatorial ANOVA II demonstrou que o efeito principal da condição foi significativo, sendo que os participantes que foram submetidos à estimulação com batimentos binaurais tiveram resultados mais altos ($F(1,115)=5.49$, $p=0.0208$). O efeito principal da sessão também foi significativo, com pontuações mais altas obtidas durante a segunda sessão ($F(1,115)=9.206$, $p=0.00298$). Houve interação significativa entre grupo e sessão ($F(1,115)=5.11$, $p=0.0256$). Para além disso, regressões lineares demonstraram que o aumento das pontuações de memória está associado ao aumento de RWE na banda de frequências beta ($F(5,114) = 5.876$, $p < 0.0001$).

Este estudo mostra que é possível quantificar os potenciais evocados auditivos corticais usando um dispositivo de EEG de grau de consumidor. Foi demonstrado que os batimentos binaurais teta de 6 Hz e beta de 20 Hz têm efeito positivo no desempenho da memória episódica, comparativamente aos

respetivos *acoustic beats.* Os participantes que foram estimulados com BBs beta tiveram melhores resultados nos testes de memória comparativamente aos que receberam estimulação com BBs teta, o que pode ser explicado pelo facto da atividade teta, característica da memória episódica, ter sido despertada durante a estimulação BB beta. No entanto, foi demonstrado que o aumento nas pontuações de memória episódica é explicado pelo aumento da RWE no ritmo beta. A resposta pós-frequência foi observada durante a exposição aos BBs teta, porém o mesmo não se verifica relativamente aos BBs beta. Para concluir, este estudo prova que os batimentos binaurais são moduladores neuronais, com envolvimento de respostas dinâmicas. Este efeito modulador da atividade cerebral pode ser a razão por trás da influência destes batimentos na memória episódica.

Palavras-chave: *Batimentos binaurais*, memória episódica, análise de wavelets, potenciais evocados auditivos corticais, *Muse*, EEG

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List of Abbreviations

AB Acoustic Beat
ABR Auditory Brainstem Response
ADHD Attention Deficit and Hyperactivity Disorder
ANOVA Analysis of Variance
AP Action Potential
ASSR Auditory Steady-State Response
BB Binaural Beat
BCI Brain-Computer Interface
CAEP Cortical Auditory Evoked Potential
CMI Cross Mutual Information
CT Computed Tomography
CWT Continuous Wavelet Transform
DRL Driven Right Leg
DWT Discrete Wavelet Transform
EEG Electroencephalography, Electroencephalogram
ERP Event-Related Potential
FFR Frequency Following Response
FFT Fast Fourier Transform
fMRI functional Magnetic Resonance Imaging
HRV Heart-Rate Variability
IIR Infinite Impulse Response
LLR Long-Latency Response
MEG Magnetoencephalography
MLR Mid-Latency Response
MRI Magnetic Resonance Imaging
MTL Medial Temporal Lobe
NIOSH National Institute for Occupational Safety and Health
PET Positron Emission Tomography
PLV Phase-Locking Value
POMS Profile Of Mood State
PSP Postsynaptic Potential
RWE Relative Wavelet Energy
SPECT Single-Photon Emission Computed Tomography
STFT Short-Time Fourier Transform
WT Wavelet Transform

1. Introduction

Binaural beats (BBs) can be understood as auditory illusions created by the brain when two coherent sounds with slightly different frequencies are presented to each dichotically [1]. There are different types of BBs, depending on frequencies that are presented, and the difference between these two frequencies is what determines the frequency of the binaural beat. For example, if the subject is listening to a 256 Hz tone in the right ear and a 250 Hz in the left ear, the beat in this phenomenon is referred to as a 6 Hz theta binaural beat. Conversely, a mix of two sinusoids presented to the same ear are called acoustic beats (ABs) and their interference result in periodic amplitude fluctuations. The perceived beat corresponds to the periodicity of the amplitude oscillations.

It has been reported that BBs have influence in psychological states and cognition. Listening to BBs has a positive effect on working memory [2]–[6], long-term memory [7], attention capacity [8], [9], anxiety and relaxation levels [10], [11]. However, there are studies reporting no relation of binaural beats to attention [12] and negative effect on short-term memory [13]. There is a need for more unification in research regarding BBs.

The divergence listed above is not the only one. There is still some inconsistency to explain the underlying brain mechanism of BB perception. It is known that a binaural beat is formed in superior olivary nuclei, then migrates to reticular formation and then to the cerebral cortex where it can be measured as a frequency following response (FFR). This effect is a tendency of the electrocortical activity to alter the power and synchronize its neural activity to the same rhythm as the external stimulus. However, the scientific community is still unsure if the synchronization to BBs happens naturally, through a mechanism called neural entrainment [14]–[16], or whether this process is caused by an increased hemispheric connectivity between auditory cortices [13], [17]. Conversely, several studies have found none of these effects [18]–[20]. In addition, studies addressing the impact of BB stimulation on brain oscillations have reported induced oscillatory activity in the EEG theta band after listening to theta BBs [14], [16], yet other studies do not support these findings [13], [19], [21], [22].

Despite the known effects of BBs on different types of memory, there is not a sufficiently wide range of studies on binaural beats and episodic memory. Episodic memory is the ability to encode and retrieve our daily personal events, mentally moving back in time and re-experiencing the past [23]. There are reports that BBs enhance selectivity in updating episodic memory traces [24], whereas other studies failed to observe this effect [25]. There are several research highlights of increased theta power during successful episodic memory performance [26]–[28]. Rozengurt et al. assumed that upregulating theta oscillations by neurofeedback training might benefit stability and persistence of episodic memory [29]. Presuming that listening to BBs has a modulating effect on brain frequencies through FFR, more specifically on theta rhythm, it is reasonable to hypothesize that binaural beats may influence episodic memory. To perform this study, a paradigm is set inspired by Rozengurt et al. research [29]. Two groups of volunteers received auditory stimulation with ABs and BBs before and during an episodic memory task, while their brain activity was measured. Time-frequency analysis was performed using Wavelet Transform to detect changes in brain oscillations.

The electroencephalography (EEG) system to measure brain activity used in this study is InteraXon's Muse headset [30], a consumer-grade EEG device designed to help people with meditation. Before proceeding to the BBs and episodic memory paradigm, it was necessary to understand if the material used was sufficiently reliable. The method to achieve this validation was to measure cortical auditory evoked potentials (CAEPs), a well-known brain response reflected by neuronal activity within auditory cortex in reaction to sound. CAEPs are quantifiable by summing up the cortical responses to an auditory stimulus with specific characteristics, presented periodically.

To recapitulate, the first part of this dissertation focuses on an exploratory study to measure CAEPs using Muse, in order to assess the device potential and the corresponding data quality. The second part and the primary goal of this study is to investigate the influence of BB on episodic memory and the effects of BB stimulation on brain oscillations, more concretely examine whether it can enhance the power of specific EEG frequencies, comparatively to acoustic beats. The following chapters include some contextualization, background theory and literature review (Chapter 2), procedures used to conduct the experiments and the corresponding analyses (Chapter 3), results derived from the methods (Chapter 4), discussion of the results and limitations (Chapter 5), and general conclusions of the study (Chapter 6).

2. Background

2.1 Human brain

The most important organ of our body is the brain. Human cortex stands out from other mammals' brains for allowing us to have consciousness and unique cognitive abilities. It is responsible for monitoring and coordinating the unconscious and automatic functioning of our organism, actions and reactions, thoughts and emotions, allowing us to have memories, feelings and senses. Studying the brain is an elaborate process, sometimes comparable to looking for a needle in a haystack: more questions are generated as the answers are given. Although writing about this organ is a never-ending book, the next paragraphs briefly describe the main aspects of the brain, its constitution and functions, and the current study paradigm. Further parts of this section focus on brain rhythms and event-related potentials from a physiological and cognitive point of view.

2.1.1 Overview of brain function

Human brain is constituted by over 100 billion neurons, electrically excitable cells of the nervous tissue, and between 40 and 100 billion of glial cells, that maintain and protect the neurons [31]. Simplifying the vast complexity and dimensionality of the brain, its major structures can be distinguished as (Figure 2.1): cerebral cortex, cerebellum, brainstem, thalamus, hypothalamus, pituitary gland and limbic system.

Cerebral cortex is the outermost area of the brain, organized topographically into distinct areas differentiated by biological properties that are integrated into functional networks, constituting 40% of the brain's total volume [32]. The largest subdivision of the cortex is the neocortex, which has 6 neuronal layers and is associated to higher cerebral functions. Joining the studies with animals, humans after brain injuries and electrical brain stimulation during surgery, it was possible to outline specific cerebral cortex regions and their link to particular functions, dividing the cerebrum into four lobes: frontal, parietal, temporal and occipital. Prefrontal cortex, the largest area of the frontal lobe, is connected to all other

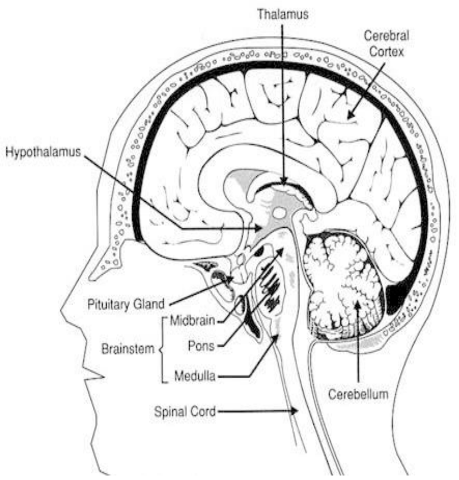

Figure 2.1 - Representation of the main brain structures. Spinal cord is not a part of the brain, but the nervous prolongation of it. Adapted from [33].

cortex regions and also limbic structures. It is associated with the processing of emotions, decision making, focusing on goals and avoiding inadequate behaviours. Another important structure found in the frontal lobe is the precentral gyrus, position of the primary motor area. Located in parietal lobe, postcentral gyrus occupies the primary somatosensory cortex, that receives sensations from all sites of our body. The temporal lobe is mainly responsible for auditory capacity, separated into smaller regions, each one specific for different sound frequencies. Visual functions and visual information processing are managed by the occipital lobe. Some sites within all the previously described brain regions that were thought to be "silent", now are identified as being part of the associative cortex. These areas play a crucial role in cognition, the process of receiving and integrating information from a variety of brain sources. [33]

Beyond the cerebrum, there are other important formations that are part of the brain. Regularly referred to as a "little brain", the cerebellum is the specialized area in sorting and processing the signals required to maintain balance and posture and to carry out coordinated movement. It is the site of rerouting and refining instructions for movement, sending impulses from the motor area of the cerebral cortex to the spinal cord, and receiving signals from the activated muscles to compare it with the information given by the motor cortex. Located posteriorly to the cerebellum, the brainstem is the location of crossover for nerve tracts running to and from the brain. This structure is responsible for autonomic functions like digestion, breathing, modulation of the cardiac rhythm, controlling the diameter of the blood vessels and the wake/sleep cycles. Above the brainstem, thalamus and hypothalamus are responsible for sorting the information from our senses and send it to the cortex. Particularly the hypothalamus is a very multifunctional structure, being the control centre for smooth muscles, sensation of hunger and thirst, induction of sleep and temperature regulation. Hypothalamus is the bridge between the two essential control systems – nervous and endocrine systems – stimulating the pituitary gland to produce essential hormones for the body functioning. Thalamus and hypothalamus are also part of the limbic system; one is a relay for sensory information and the other translates the emotion into physical response. The limbic system is the brain circuit that manages emotion, behaviour, memory and olfaction. Its other constitutes are amygdala, connected to olfactory system and responsible for processing emotional information and sending it to cortex, and hippocampus, playing a main role in consolidation of short-term memories. [33]

Despite the notions described previously, nowadays research focuses in finding a formalization for brain-behaviour and brain-disease relationships. Communication between individual neurons, neuronal populations or anatomically segregated brain regions can be understood as a pattern of anatomical links, networks of brain-rhythm interactions, statistical dependencies or causal interactions. This set of patterns is called brain connectivity, representing the true complexity of the nervous system. Brain function is increasingly understood thanks to neuroimaging techniques, which advanced dramatically during the last decade. The combination of several brain imaging methods (Figure 2.2) permitted to create brain network maps with properties that have been identified with consistency in all modalities of neuroimaging. It is now possible to trace abnormal brain activity and identify dysfunctional circuits for a better disease diagnosis. Mapping brain circuitry in a given disorder increases the potential of therapeutic modulation in disease treatment. [34]

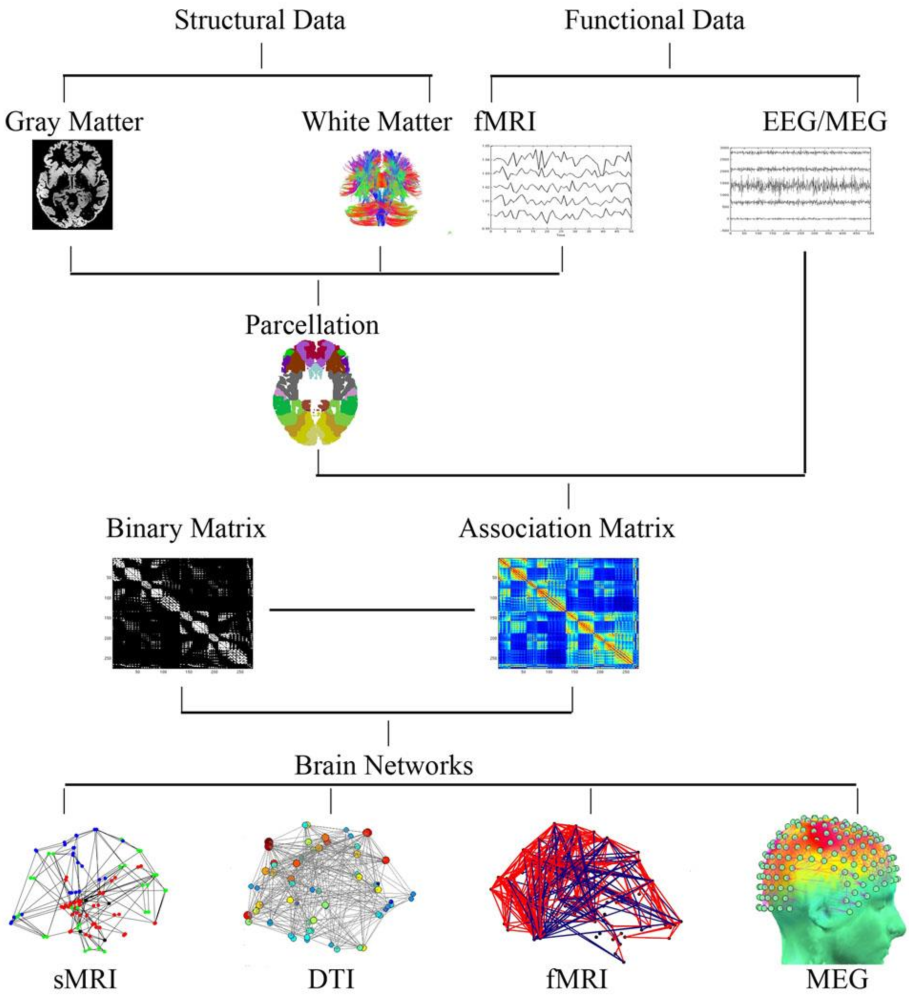

Figure 2.2 - Brain network construction: the combination of structural (anatomical) and functional data together with computation techniques allow to build networks from brain regions and pairwise associations. Source: [34].

2.1.2 Brain rhythms

Brain rhythms, also referred to as brain waves, refer to a phenomenon that results from the synchronized activity of large numbers of neurons. The neural synchronization occurs with different frequencies, amplitudes and phase characteristics. These properties can be extracted applying time-frequency analysis and used to describe different levels of awareness, vigilance, distraction, stress, relaxation and sleep states.

There are five kinds of typical oscillations: alpha, beta, gamma, theta and delta (Figure 2.3). Brain waves were first recorded and observed in 1924 by Hans Berger, the father of electroencephalography, and in 1929 his first paper on EEG was published where the terms alpha and beta waves were used for the first time [36]. The EEG technique will be explained in more depth in Section 2.3. The rhythm of alpha wave, also known as “Berger wave”, varies within the range of 7-13 Hz and was first detected over the occipital lobe when the subjects were relaxed or closed their eyes. Further studies spotted alpha waves during a wakeful state when the person is calmly resting, reflecting passive mental activity. Even though alpha distribution is widespread, the definition of alpha rhythmicity presumes a spatial distinction. For example, larger amplitude frontal alpha often occurs as subjects become calmer, by employing relaxation or meditation techniques. Maximal occipital alpha oscillations occur within closed

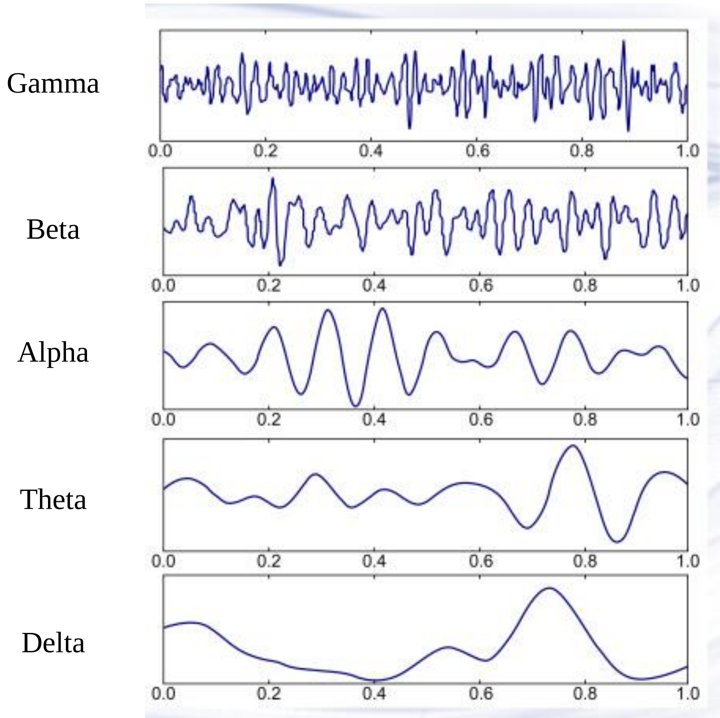

Figure 2.3 – Brain rhythm pattern in a normal adult: gamma (>30 Hz), beta (13-30 Hz), alpha (7-13 Hz), theta (4-7 Hz) and delta (0.5-4 Hz). Adapted from [35].

eyes condition. Alpha mu rhythms, also known as Rolandic, are localized above the sensory-motor strip of the cortex and are supressed during tactile stimulation and enhanced during muscular relaxation. It should be noted that mu rhythms can be found in both right and left hemispheres, however they are independent and produced by different generators [37].

Berger observed that alpha rhythm decreases or attenuates upon eyes opening and is replaced by beta waves, higher frequency rhythms between 13 and 30 Hz. Beta waves are common during active mental activities, concentration, attention focus or tension. There are three different ranges to classify beta waves: low beta or beta I waves (13-15 Hz), associated with calm and introverted concentration; mid-range beta or beta II waves (15-20 Hz), linked to upturns in energy, anxiety and performance; high beta waves or beta III (20-30 Hz), associated with significant psychological tension, paranoia, high anxiety, energy and arousal levels [38]. Although beta rhythm is observed over whole brain, maximal beta amplitude can usually be measured in frontocentral regions. Thus, at least two beta rhythms can be distinguished – frontal beta rhythms (peaking below 20 Hz), which emerge in cognitive tasks and decision making, and Rolandic beta rhythms (peaking at 20 Hz), observed in sensorimotor cortex following motor actions [39]. Rhythms above beta frequency are known as gamma rhythms, being difficult to record for having low energy. Gamma waves are thought to be interventive in temporal binding, which can be explained as temporal correlation of activities of neural elements. There is also an agreement upon synchronized oscillatory activity in the gamma range when subjects experience a consistent visual percept [40].

Slower rhythms play a fundamental role in our brain. Theta waves are the slowest oscillations in the normal waking state, varying from 4 to 7 Hz. They are thought to be AM carriers for gamma oscillations and to be associated with memory and frontal lobe events. These rhythms normally arise during relaxed wakefulness, for example in meditation practices, or emergence of drowsiness. There are two kinds of theta oscillations that deserve distinction, namely frontal midline theta rhythm and hippocampal theta rhythm. Despite the fact that low voltage theta rhythm can appear in any brain area, frontal midline and hippocampus are the sites where the theta waves are more prominent. It is hypothesized that hippocampal theta rhythm is involved in memory programming and retrieval, enabling coding and decoding of hippocampal learning in the cortex. Frontal midline theta rhythm, together with hippocampal, is responsible for processing of memory and emotion. Frontal midline theta oscillations are most prevalent in tasks where the subject is engaged in focused, but also relaxed, concentration. For example, working memory has been repeatedly stated to associate with frontal midline theta rhythm. This activity is also aroused during situations associated with operations of cognitive control, like conflict detection and monitoring. In terms of scalp topography, the theta rhythm power is maximal at frontal position of midline sagittal plane of the skull, with an average around 6 Hz [41]. Following theta, the slowest recorded brain rhythm in humans are delta waves. These oscillations have high amplitudes and the frequency range between 0.5 and 4 Hz. Delta waves are associated with deep relaxation levels and restoring sleep, being most detected during stage 3 of non-rapid eye movement sleep.

Our brain generates permanently a variety of rhythms, spread through a range of frequencies and anatomical locations. It is important to have a track of the changes in neuronal network rhythms as it can be a mark of some type of abnormality or brain disease. Berger observed that alpha rhythm slowed from normal frequencies in presence of tumours [42]. Reduction in alpha waves and a very low amplitude background EEG rhythm were also observed in patients with Huntington disease. In addition, reduction of alpha rhythm is associated to Alzheimer dementia, together with disorganization in theta rhythms [34]. Alpha waves that present frontal dominance or an unusual large amplitude can be associated to mental retardation or epilepsy. Unilateral attenuation of alpha rhythm sometimes occurs due to lesions in parietal or temporal lobes [43]. Delta rhythm is correlated with brain injuries, learning problems, inability to think, and severe attention deficit and hyperactivity disorder (ADHD). If this wave is suppressed, it leads to poor sleep and inability to rejuvenate the body and revitalize the brain [38]. Suppression of beta waves leads do ADHD, daydreaming, depression and compromised cognition [38]. Regarding theta rhythm, high amplitudes in theta oscillations at frontal locations were observed in patients with closed brain injury (Figure 2.4). EEG acquisition with eyes closed condition, 5 days after the injury, evidenced a spectral peak at 6.1 Hz over frontal areas. Another example of abnormal theta activity was observed in a subgroup of patients with ADHD, who exhibit poor social relationships and inadequate behaviour: the EEG spectra presented an extremely high and sharp peak within theta band [41].

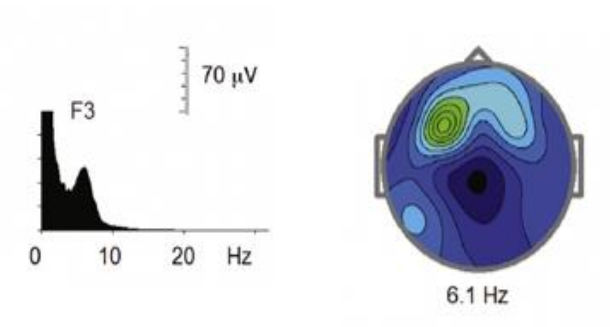

Figure 2.4 - Abnormal theta rhythm in closed brain injury. On the left side the EEG spectra present a peak within theta band. The right image presents spectral map at 6.1 Hz, noting the abnormal prominence of theta activity in frontal lobe. Adapted from [41].

2.1.3 Event-related potentials

When a specific cognitive, sensory or motor stimulus is presented, spontaneous brain activity is disturbed and a stereotyped electrophysiological response is generated. This response is called event-related potential (ERP). Each ERP component is either a positive or a negative peak that represents a sum of potentials generated in widely distributed cortical sources, reflecting the phases of information processing in the sensory-related neuronal networks, in the networks of cognitive control, memory and affective systems of the brain. ERPs can be measured using electroencephalography, which will be described in depth in Section 2.3.

There are mainly two types of electrical activity produced by the neurons: action potentials (APs) and postsynaptic potentials (PSPs). APs are discrete voltage spikes that travel over neurons, leading to the release of neurotransmitters through axon terminals. When the neurotransmitters bind to receptors on the membrane of the adjacent cell, a graded change in the voltage across the cell membrane is generated as a result of opening or closing of ion channels, and a PSP is raised. Any ERPs recorded from the scalp more than 20 milliseconds after the stimulus onset are originated by PSPs rather than APs. Large population of neurons do not fire at exactly the same time, usually presenting a gap of few microseconds in between. This is sufficient for the electrical signals not being able to summate, the reason for inability to detect APs via scalp electrodes. [44]

Scalp ERPs arise mostly from pyramidal cells (Figure 2.5). These cells are positioned perpendicularly to the cortical surface: the apical dendrite is oriented in the direction of the cortical surface and the cell body and basal dendrites head to the white matter (Figure 2.5b). When an excitatory neurotransmitter is released at the apical dendrite of a cortical pyramidal cell, a small dipole is created (Figure 2.5a): positively charged ions flow from the outside into the cell, producing a net negativity in the outer space of the apical dendrites; conversely, current flows out of the cell body and basal dendrites, generating a net positivity at that site. In order to the dipoles from the individual neurons to sum and become measurable at the scalp (Figure 2.5c), a set of conditions must be fulfilled [44]:

- Large numbers of neurons (thousands to millions) must be aroused simultaneously.
- The individual neurons must present the same orientation.
- The postsynaptic potentials for the majority of the neurons must arise either from the apical dendrite or the cell body and basal dendrites.
- The direction of the current flow of most of the neurons must be the same, otherwise they would cancel each other.

An example of ERP waveform is presented by Figure 2.6. The EEG is recorded from a set of scalp electrodes, while several time-locked sensorial stimuli are presented. The ERP is isolated from the ongoing EEG by averaging the EEG segments of the response following each stimulus or event. Having a large number of trials, brain activity that is unrelated to the event will average to zero, and the activity that is time-locked to the stimulus will sum up and remain in the average. The resulting averaged ERP waveform present several positive or negative deflections, which are given the name of peaks, waves or components. The nomenclature P or N indicates that the component is either positive or negative, following with a number that represents the timing of the peak. For example, P1 denotes the first positive peak of the waveform, while P100 is the component corresponding to the latency of 100 milliseconds. The negative and positive components may appear inverted, depending on the location and orientation of the generator dipole with respect to the active recording electrode, or the site of the reference electrode.

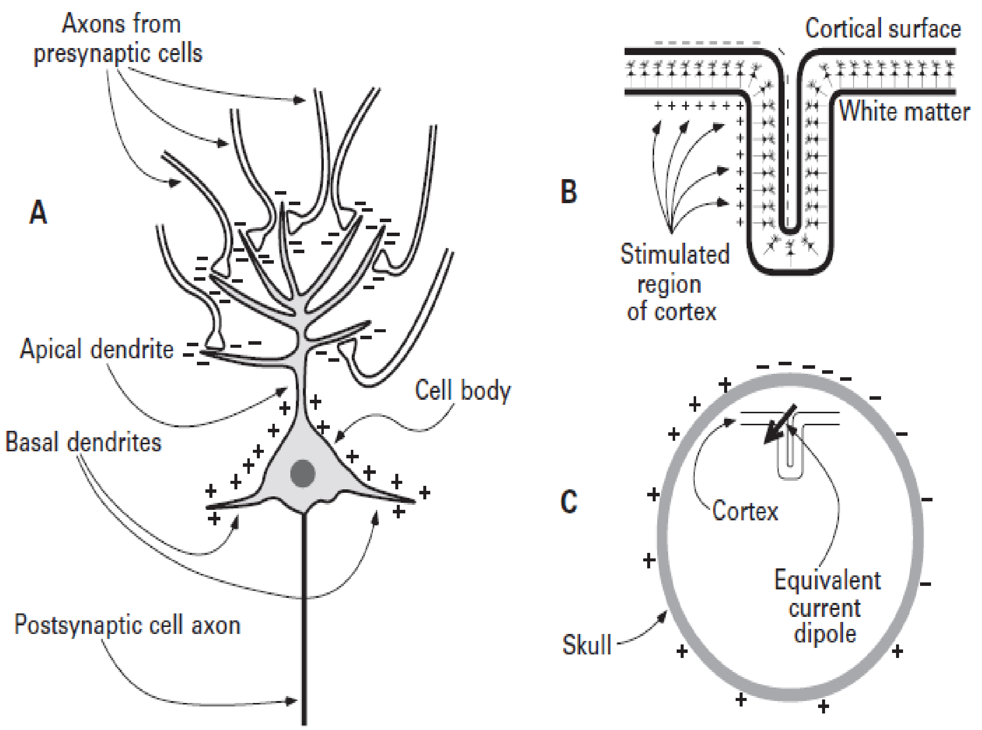

Figure 2.5 - Principles of ERP generation: a) schematic pyramidal cell during neurotransmission; b) folded sheet of cortex with dipoles produced by several pyramidal cells; c) single equivalent current dipole. Adapted from [44].

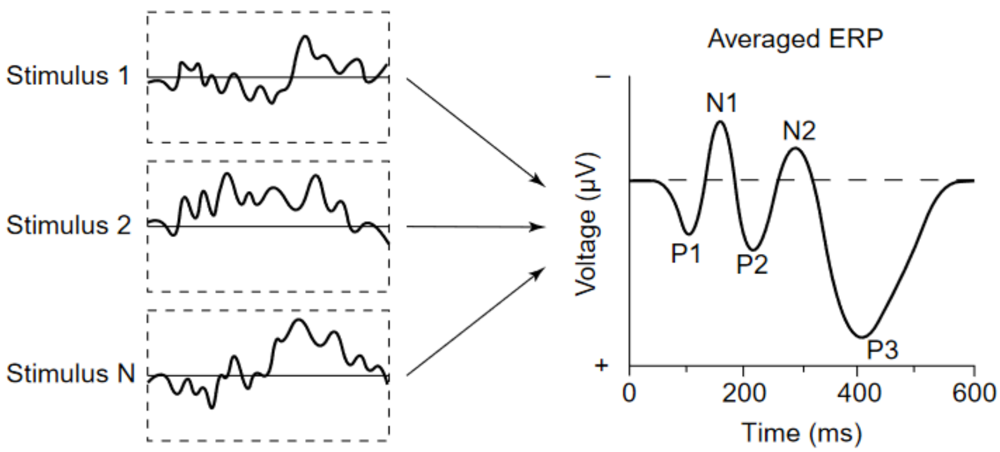

Figure 2.6 - Extraction of the ERP waveform from ongoing EEG. Adapted from [46].

A specific type of ERPs particularly relevant for this study are cortical auditory evoked potentials (CAEPs). These are a subtype of auditory sensory responses that can be divided into auditory brainstem responses (ABRs), mid-latency responses (MLRs) and long-latency responses (LLRs), that correspond precisely to CAEPs. A typical sequence of auditory sensory components is presented by Figure 2.7. ABRs are the first series of 10 milliseconds of distinctive peaks that arise when the auditory stimulus has a rapid onset, such as a click. The sequence of peaks is denoted by Roman numerals and represent the information that flows from the cochlea through the brainstem into the thalamus. Following ABRs, MLRs are the responses between 10 and 50 milliseconds, originated within medial geniculate nucleus of the auditory thalamus and primary auditory cortex. Further, LLRs or CAEP represent the cortical auditory response and are usually constituted by the peaks P50 or P1, N100 or N1, P160 or P2, and a small amplitude peak P300 or P3 [44]. The component P1 peaks at 50 ms and is thought to be originated mainly from the primary auditory cortex, with contributions from the hippocampus, lateral temporal cortex and neocortical areas. The N1 peak appears around 100 ms and has three overlapping components with distinct generators: a frontocentral component that peaks at 100 ms; a vertex-maximum component subdivided into two peaks, positive peak around 100 ms and negative peak around 150 ms, originated within auditory association cortex of the superior temporal gyrus; and the third component peaking around 100 ms, thought to be related to general transient arousal to increase sensory and motor responses to sound [45].

The ERP technique provides an instantaneous millisecond-resolution measure of neuronal activity. It has been a particularly useful tool in cognitive neuroscience by substituting reaction-time measurements, which did not present information about what happens in between the stimulus and the response. In an ERP experiment, the stimulus elicits a continuous ERP waveform that represents the neural process from the instant the stimulus is presented until the response is generated. In addition, the ERP technique offers a possibility to isolate specific cognitive processes via scalp voltage distributions, that can be used to estimate the neuroanatomical location of the process [46]. ERPs are potentially

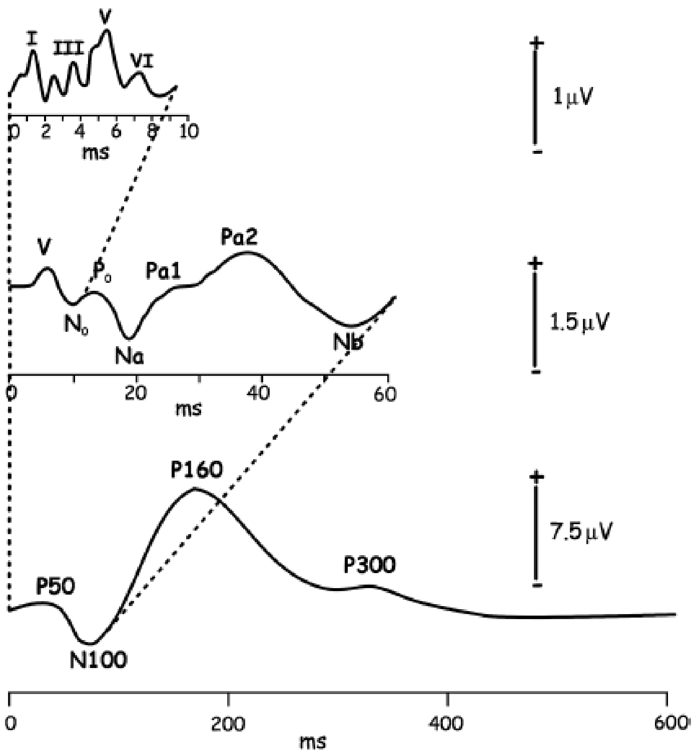

Figure 2.7 - Auditory sensory components: auditory brainstem response (top); midlatency response (middle); long-latency response (bottom). Source [44].

valuable as biomarkers in medical applications and pharmacological treatments. In other words, ERPs can be used to obtain some specific insights about the brain function that is impaired in neurological and psychiatric diseases. This information can be used to design a personalized treatments or evaluate the impacts of a specific drug in the brain, determining which medications are most likely to be efficient for a particular patient. Certain changes in latency and amplitude of ERP components have already been detected in people with psychiatric and neurotic disorders, such as alcohol dependence syndrome, schizophrenia, bipolar affective disorder, depression, phobia, anxiety, panic disorder, post-traumatic stress, obsessive compulsive disorder and dissociative disorder [47]. To conclude, the ERP method is relatively inexpensive and can be easily recorded in animal models or clinical settings, providing reliable and sensitive measures of individual differences. This is an evidence of the great potential of ERPs for use as biomarkers.

2.2 Episodic memory

The ability of situating autobiographical events in space and time is called episodic memory, representing a small part of a great sphere of memory domain. It is the most personal type of memory, giving us the recollection of our own individual experiences. Episodic memory system is complex and involves neuronal circuits within medial temporal lobe (MTL) and several cortex structures, with theta rhythm playing a crucial role in successful episodic memory performance. Binaural beats are modulatory tools that were demonstrated to have an effect on several types of memory and mental states. In this section, the definition of episodic memory will be presented, separating it from other types of memory. A discussion about brain mechanisms underlying episodic memory system will proceed. Regardless of unavailability of literature comprising episodic memory and BBs, the end of this section will review how BB influence mood and cognition.

2.2.1 Definition

Episodic memories are consciously recalled episodes associated to personally experienced events. This type of memory is related to autobiographical memory which refers to recollections about a person's own life. There are three crucial notions associated to episodic memory – self, autonoetic awareness and subjectively sensed time. The person (self) has the ability to become aware of his/her existence in subjectively perceived time (autonoetic awareness), by travelling mentally to the personal past or future (subjectively sensed time) [23]. Moreover, recollection of episodic memories is embedded in a complex conceptual system that involves a filed or a third-person observer perspective [48].

In the sphere of psychological research, episodic memory was first defined by Endel Tulving in 1972. Tulving's work influenced academic research due to his focus in defining differences between recollection of a particular experience at given place and time, versus retrieval of factual evidence from general knowledge. This way, the definition of episodic memory was introduced as a contrast to the concept of semantic memory. But before advancing to this characterization, the concepts of sensory memory, short-term memory and long-term memory need to be presented. Sensory memory allows us to process and recall information from our visual, auditory or haptic senses. Sensory information is stored in sensory memory during less than 1 second before it gets transferred to short-term memory. Conversely, short-term memory is the capacity to retain a small amount of information, instantly available in an active state during short period of time (usually less than 1 minute). It is important to make a mention about working memory: despite some researchers denoting this type of memory as the same as short-term memory, it is possible to characterize it in three, slightly incompatible ways. Working memory is defined as short-term memory applied to cognitive tasks, as a multi-component system that retains and manipulates information in a short-term system [49]. Nevertheless, in order for short-term information to be transferred and stored in long-term memory, rehearsal is needed.

Long-term memory differs from the short-term memory in duration and in capacity. Information in short-term storage decays from this type of storage as a function of time. Regarding capacity, the limit of how many items short-term memory can hold is way less than long-term storage [49]. There are two types of long-term memory, procedural and declarative, that both relate to an individual's present experience or behaviour influenced by earlier experience. Procedural memory is demonstrated by performing a task that involves a skill, usually requiring expensive periods of practice until there is an absence of thought from the execution. Procedural storage is used for actions like walking, riding a bike or dancing. Alternatively, declarative memory, or also called propositional memory, requires directed attention and can be acquired in a single brief occasion. Finally, this discussion reaches the point when episodic and semantic memory are distinguished.

Episodic and semantic memory are both types of declarative memory: one is involved in the recording and later retrieval of memories of personal events and doings; the other is related to the knowledge of the world that is independent of an individual's identity or past. The information registered in both systems is received from the external environment through senses or internally by thoughts and imagination. However, the immediate source of the information is received differently by the two systems. Semantic system stores the knowledge after the content of an event is understood and comprehended. It is unlikely that a meaningless and uninterpreted change within perceptual environment is registered to the semantic memory, yet it seems to be sufficient for episodic system to record that event. While semantic memory is referred to as a second-hand knowledge, episodic memory is more direct and immediate. The perceptible properties of stimuli apprehended immediately by the senses can be recorded and retained by the episodic system. [50]

It is reasonable to presume that the affective component plays a much more important role in the episodic rather than in the semantic memory. Personal experiences are generally emotional, taking place while the person is in a certain mood. Thus, the retrieval of information of episodic memory is conditioned by the emotional state. This also plays a role in the context dependency of the episodic system, where the contextual retrieval links are present. Moreover, while the access to information in semantic system is automatic, the process is deliberate and requires a conscious effort to enter the episodic storage. There is a tendency to change the information while retrieving and updating, which highlights the vulnerability of the episodic system. [50]

There are different putative tests of episodic cognition. Episodic memory must code spatiotemporal relations, being assessed through The What-Where-When test. It can be performed by hiding objects in some place at different occasions and then recall which objects (What) were hidden in which locations (Where) and on which of the occasions (When). Conversely, episodic memory retrieval may occur unlinked or in response to an internally generated cue, which can be tested by a Free Recall Test. Tulving saw that the contribution of episodic cognition to memory was because the subjects simply knew "on some basis" that the item was on the list rather than remembering an item's occurrence on the list (cued remembering) [51]. Episodic memory may be also assessed by a Source Memory Test, the ability to retrieve the source of remembered facts. This comes from an assumption that memory for focal elements, equivalent to semantic memory, and source memory for contexts, equivalent to episodic memory, are independent. Episodic memory must not be deliberately encoded, what can be assessed by The Unexpected Question, based on the idea that deliberate encoding of something may lead it to be stored as semantic rather than episodic memories [52].

Cheke and Clayton [53] concluded that not all of the tests described previously are necessarily testing the same thing. It was predicted that to the extent to which different tests are assessing the same psychological process, performance across the various tests should be positively correlated. Free Recall test and What-Where-When test were positively correlated, What-Where-When had a quadratic relationship with Unexpected Question/Source Memory, but there was no relationship between Free Recall and Unexpected Question/Source Memory. It is important to study and choose the right test to be performed, depending on which bibliography the results will be compared to.

2.2.2 Brain mechanisms of episodic memory

Anatomical and neuropsychological studies in animals and humans reveal that the circuitry of the medial temporal lobes and its interaction with specific distributed cortical and subcortical structures are associated to several components of perception and cognition, including episodic memories. The first evidence of the location responsible for a specific function in the brain arises from studies of the effects of brain damage. To introduce which mechanisms our brain uses to encode and retrieve episodic memories, the famous case of Henry Molaison will be presented before "diving" more deeply into the neurocircuitry and brain frequency basis.

Henry Molaison (better known as patient HM, to preserve anonymity while he was alive) presented a complete anterograde amnesia after having a surgery to remove regions of the brain that were responsible for his daily epilepsy seizures. He demonstrated an incapability to form memories regarding new events in his life after the surgery, such as for example, not being able to remember who he met 5 minutes previously. He was able to recollect memories from his childhood and youth past, and his working, semantic and procedural memory systems also seemed to be preserved. All of this demonstrates that only his episodic storage system was impaired. The structures that were removed during the surgery included the anterior two-thirds of the hippocampus, the entire entorhinal cortex and parts of the perirhinal and parahippocampal cortices, as well as amygdala and white matter fibre connections of these regions (Figure 2.8). It was later demonstrated that the majority of these structures, together with others, form a circuit responsible for episodic memory system. [54]

After the evidence of involvement of hippocampus in memory processes presented in brain lesions studies, research became focused in finding activation of this region through neuroimaging techniques such as positron-emission-tomography (PET), that measures uptake of radioactive glucose or oxygen in brain regions, and functional magnetic resonance (fMRI), that assess changes in blood oxygenation and

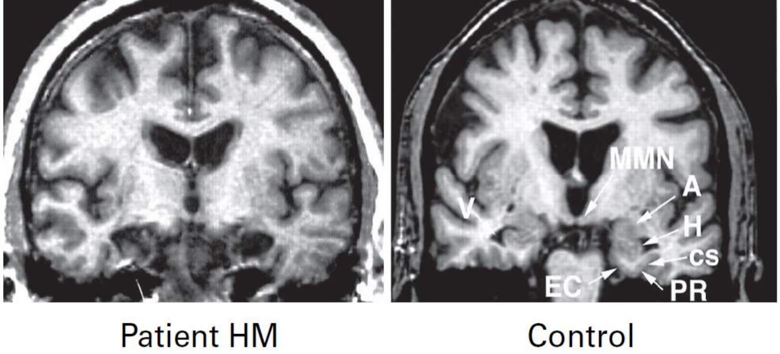

Figure 2.8 – Comparison of MRI scans between patient HM and control. The right scan presents the structures before they were removed or became missing after patient's surgery: hippocampus (H), entorhinal cortex (EC), perirhinal cortex (PR), amygdala (A), medial mammillary nucleus (MMN), collateral sulcus (cs) and ventricle (v). The left scan, therefore, shows the absence of these structures. Adapted from [54].

flow associated with neural activity. Not only activations in hippocampus were found, but a broad of other regions responsible for formation of episodic memories were identified: MTL, which includes hippocampus together with entorhinal, perirhinal, and parahippocampal cortices; neocortical regions, such as prefrontal and retrosplenial cortices; and parietal cortex. Figure 2.9 presents a scheme of the neurocircuitry within the MTL system. The entorhinal cortex provides the majority of cortical input to the hippocampus. The medial entorhinal cortex, responsible for encoding the spatiotemporal trajectory through space, receives a selective input from postsubiculum, and a converging input from neocortex via postrhinal cortex. In turn, lateral entorhinal cortex encodes events at specific time points by receiving input through perirhinal cortex. The circuits of the hippocampus, including regions of dentate gyrus, CA1 and CA3, play an essential role in encoding associations between the elements of episodic memory. Dentate gyrus receives input from both entorhinal regions and projects it to region CA3, which transfers the information to CA1. Moreover, neurons along the dorsal to ventral levels of entorhinal regions send topographic input to neurons along the septal to temporal portion of region CA1, which projects the information back, directly or indirectly, to the respective entorhinal region. The medial septum is the "glue" between the hippocampus and the two parts of the entorhinal cortex, providing synchronization between these structures through the theta rhythm. [54]

Several studies associate the presence of theta oscillation during successful episodic memory performance. Assuming that episodic memory is dependent on spatiotemporal context, Staudigl et al. [28] investigated theta oscillatory activity during encoding, using movies to induce context-dependent memory effects. The stimuli consisted of 360 unrelated German nouns and 360 movie scenes, that were paired and assigned in context-match condition and context-mismatch condition. The subsequent memory effects correspond to differences between hits and misses, between the match and the mismatch condition in terms of associated activity at encoding. The study revealed that these effects were evident in theta power and in theta-to-gamma cross-frequency coupling, which have both been suggested to play

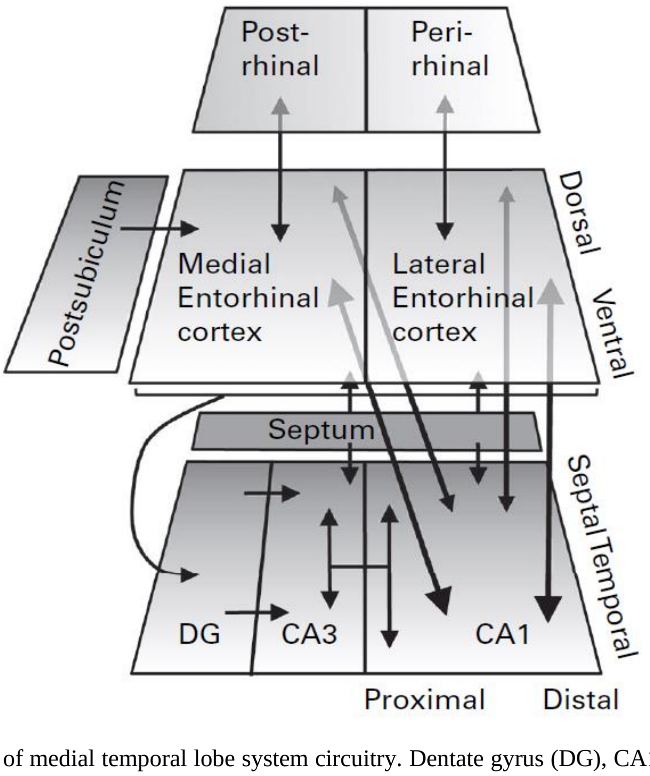

Figure 2.9 - Schematic model of medial temporal lobe system circuitry. Dentate gyrus (DG), CA1 and CA3 are hippocampal regions. Source [54].

a key role when integrating a memory item with its spatiotemporal context. Klimesch et al. examined task-related band power changes in the theta and alpha bands during encoding in an implicit memory paradigm [26]. The results showed significantly higher theta power during the encoding of those words which could be remembered in the later recall task, compared with words which could not be remembered later. Sato and Yamaguchi experimentally investigated scalp EEG during performance of the object–place memory task with voluntary eye movement [27]. Their results successfully demonstrated that memory recall is characterized by an increase in theta power and coherence and an emerging of multiple theta synchronization networks, suggesting that human theta dynamics are in common with rodents in episodic memory formation. An intracranial EEG study revealed that 3 Hz slow-theta oscillations exhibited higher power during successful episodic memory encoding and was functionally linked to gamma oscillations [55]. Similar patterns were not observed in 8 Hz fast-theta oscillation. Rozengurt et al. hypothesized that upregulating theta power during early stages of consolidation might benefit to episodic memory stability and persistence [29]. The participants performed a memory encoding task, consisted of viewing pictures of objects, several free recall tests and theta neurofeedback session. Free recall assessments indicated a benefit of theta neurofeedback to memory, relative to low beta neurofeedback or passive control conditions. The degree of benefit to the memory was correlated with the extent of theta power modulation, suggesting that theta enhancement may provide optimal conditions for stabilization of new hippocampus dependent memories.

2.2.3 Binaural beats: effects on memory, cognition and mood

Binaural beats (BBs) are auditory illusions elicited by two coherent sound waves with nearly similar frequencies that are presented dichotically, that is, to each ear respectively [1]. The resulting beat is a sensation reflected by the convergence of neural activity from both ears in central binaurally sensitive neurons of the auditory pathways of the brain. The BB frequency corresponds to the difference of the frequencies perceived by each ear: for example, if we present a 256 Hz tone to the right ear and a 250 Hz to the left, the beat in this phenomenon is generated within the brain and is referred to as a 6 Hz binaural beat (Figure 2.10). These two presented frequencies are called carrier tones. To complete the definition, binaural beats should not be confused with acoustic beats (ABs). An acoustic beat is the mix of two sinusoids presented to the same ear and their interference result in periodic amplitude fluctuations, as represented by Figure 2.10. The perceived beat corresponds to the periodicity of the amplitude oscillations. Binaural beats are thought to be an influence on memory, attention, anxiety, depression and relaxation. Further paragraphs discuss all these effects.

There are several reports that BBs have influence on working memory. Kraus and Porubanova showed that 12-minute listening to 9.55 Hz alpha BBs had a positive effect on working memory capacity, measured by automated operation span task [2]. Another study demonstrated that listening to

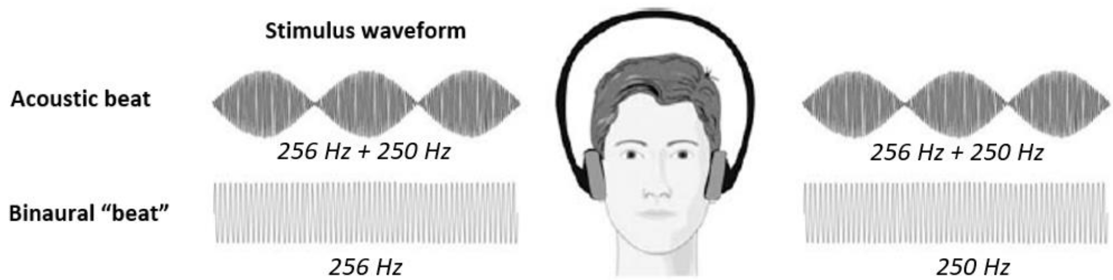

Figure 2.10 - Comparison between acoustic beats and binaural beats. Adapted from [80].

15 Hz beta BBs increases accuracy in delayed match-to-sample visuospatial working memory task, compared to the condition of absence of auditory stimulus [3]. In turn, 5 Hz and 10 Hz BB produced decreases in accuracy. The increase in performance can be understood by the fact that 15 Hz BB may increase neural synchronization within beta band, which is associated with active concentration [56]. The same team determined that listening to 15 Hz binaural beats during an N-Back verbal working memory task increased the individual participant's accuracy [4]. This study also demonstrated that 15 Hz BB produced the highest change in theta band frequency power magnitude, which relates to the network rhythm behind the processes of working memory. Another study reports a decrease in theta activity induced by BB stimulation of 14 Hz for 10 minutes, in patients with Parkinson's disease [5]. Nevertheless, the researchers saw an improvement in working memory performance in cognitive PD-CRS test. Despite the positive effect of BB stimulation within beta band on working memory, other researchers observed contrary results. Ortiz et al. showed that participants performed significantly better on a word recall task when listening to 5Hz BB when compared to 13Hz [6].

It was also showed that binaural beats affect long-term memory [7], with 20 Hz beta BB stimulation producing a greater proportion of correctly recalled words than 5 Hz theta BBs. In addition, theta BBs produced a negative effect on the word recall. Regarding short-term memory, Wahbeh et al. reported a negative effect after 30 minutes of 7 Hz theta BB stimulation [13]. The Rey Auditory Verbal List Test demonstrated a decrease in immediate memory recall in experimental condition, comparatively to pink noise control condition. Shekar et al. [57] registered no significant effects of alpha (10 Hz) or gamma (40 Hz) BBs on short-term memory, whereas they observed a reduction in auditory and visual time responses associated to BB listening.

There are few studies regarding BBs and episodic memory. It was demonstrated that the size of visual feature binding costs, indicating the effort of integrating combinations of shape and colour of the stimulus to perceive an object, was considerably smaller after 10-minute listening of high frequency 40 Hz gamma BBs, comparatively to 340 Hz constant control tone [24]. This proves that BBs enhance selectivity in updating episodic memory traces. Conversely, a graduate dissertation did not report effects of BBs on episodic memory [25]. It was observed that listening to 5 Hz and 7 Hz theta BBs did not produce improvements in word free recall performance, compared to 5 Hz isochronic tones. More findings about influence of binaural beats on episodic memory are needed.

Research on BBs and attention has shown influence of gamma BBs on concentration. Hommel et al. observed a positive effect of 40 Hz gamma BBs on cognitive flexibility: the response-compatibility effect was more pronounced after exposure to BBs than within the control 340 Hz constant tone condition [8]. A further study, using the same control and stimulation conditions, revealed a significant impact on the global precedence effect, suggesting higher focus of visual attention [9]. Nonetheless, gamma BBs did not lead the participants to supress irrelevant information in working memory. Crespo et al. reports no significant differences in attention capacity and effectiveness after 20-minute stimulation with 4 Hz theta and 16 Hz beta BBs, compared to pink noise as control condition [12]. These findings suggest that only BBs within the range of gamma frequencies, more particularly 40 Hz, have a positive influence on attention function.

Regarding anxiety and relaxation levels, BBs were observed to have beneficial effects. It was showed that BBs are useful to reduce preoperative dental surgery anxiety [10]. When local anaesthetic was given, the patients in the experimental group received 10-minute stimulation with 9.3 Hz alpha BBs, while control group received no stimulus. The degree of anxiety was recorded using visual analogue scale, before and after listening to BBs. The results reveal a significative reduction in anxiety in participants who listened to BBs, whereas the control group presented no changes. McConnel et al. investigated if BBs could influence relaxation level and heart rate variability (HRV) during post-exercise period [11]. The participants visited the lab two times: one visit included varying theta BBs (masked with pink noise) and the other control pink noise, while HRV was continuously measured. Regarding

BB visit, the subjects reported greater relaxation and HRV analysis suggested an increased parasympathetic activation and sympathetic withdrawal, compared to the control visit. These are evidences that BBs may modulate autonomic arousal and behavioural variables, such as anxiety and relaxation.

Binaural beats were showed to be associated with improvements in vigilance and mood [58]. The participants received 30-minute stimulation with 16 Hz and 24 Hz beta BBs simultaneously, and another stimulation with 1.5 Hz and 4 Hz delta/theta BBs, also at once, while performing a vigilance task. The results suggest that beta BBs were associated with more correct target detections and reduction in the number of false alarms, compared to delta/theta BBs. Profile of Mood State (POMS) revealed the association of beta BBs with smaller increases in task-related confusion and fatigue. Moreover, delta/theta BBs were associated to a subjective impairment ability to concentrate. In counterpart, beta BBs were linked to less negative mood, comparatively to theta BBs. A study performed by Wahbeh et al. registered an increase in depression after listening to 7 theta Hz BBs, measured by POMS [13]. From these conclusions, it can be speculated that theta BBs have a negative effect on mood.

Nevertheless, binaural beats represent a non-invasive method that can affect cognition, memory, arousal levels, relaxation and mood states. Although the discrepancy between some studies, research should continue to focus on this technology to provide a better understanding of its effects to design new and efficient applications. Moreover, additional studies should be performed to investigate if binaural beats can affect episodic memory.

2.3 Electroencephalography

Electroencephalography is frequently referred to as "window on the mind", as it offers the possibility to observe and decodify the electrical events within our brain [59]. First human EEG recording was performed in 1924 by Hans Berger [60], and by 1950 this technology was already widely used with important applications in neurosurgery, neurology and psychology. Nowadays, this tool stands out for having the highest temporal resolution among other more recent neuroimaging methods. In this chapter, an overview of EEG technique will be presented, covering its advantages, and technical and methodological considerations. The discussion will follow about the most recent EEG technology - low-cost portable consumer-grade EEG devices - and its applications in research. Finally, applications of EEG technique will be presented in the context of the study of brain processes underlying the perception of binaural beats.

2.3.1 Overview of the technique

Electroencephalography is a unique and efficient tool to measure electrical brain activity over time. The use of this technique has been increasing in neuroscience, neurology and psychology together with other more sophisticated methods, such as computed tomography (CT), magnetic resonance imaging (MRI), nuclear medicine imaging (PET and SPECT), functional MRI (fMRI) and magnetoencephalography (MEG). EEG is distinguished among other imaging techniques for being the only broadly available technology with sufficient temporal resolution to detect the smallest dynamic changes, up to 1 millisecond in duration. Alternatively, while radiological imaging and MRI provide accurate anatomical information with high resolution, EEG and MEG offer poor spatial resolution. Magnetoencephalography consists of recordings of the magnetic field generated by brain current sources located tangentially to the scalp, whereas EEG measures electrical activity from neurons oriented perpendicular to the scalp. Commonly used brain imaging systems are non-portable, bulky and require expensive hardware and software tools. In addition, CT, PET and SPECT systems rely on the use of ionizing radiation. EEG technology offers a great advantage for being portable, non-invasive, safe and affordable. The comparison of the main aspects of EEG and other brain imaging techniques is summarized in Table 2.1.

EEG from an electrode channel measures continuous voltage fluctuations between two given points, reflected by the amplitude or height on the page. These voltage variations are originated at large scales of ionic current within thousands and millions of neurons in cortical tissue. An EEG recording is a mixture of waves of different frequencies and amplitudes, with different contributors from various locations in the brain. One important aspect in EEG interpretation is the ability to decompose the mixed signal into simpler waves, according to their frequencies. This is performed using Fourier based methods, a standard tool in EEG analysis to extract spectral features. Each spectral component can be defined in terms of its amplitude A_{nm}, frequency f_{nm} and phase ϕ_{nm}. The EEG voltage $V_m(t)$ measured between a pair of electrodes *m* can be expressed as a sum over *N* frequency components, as described by Equation 2.1 [59]:

$$V_m(t) = \sum_{n=1}^{N} A_{nm} \sin\left(2\pi f_{nm} t - \phi_{nm}\right) \tag{2.1}$$

To localize an EEG event, we need to know in which position the electrode in question was placed in the scalp. The design of the electrode placement and naming usually follows the international 10-20 system (Figure 2.11a) or modified 10-20 system (Figure 2.11b), with a total of 21 electrodes. Both of the systems are quite similar and are in use nowadays. The difference is that in modified 10-20 system four of the electrode positions have been renamed, which are shown shaded in Figure 2.11b. The terminology 10-20 is based on the method of measuring the distance between nasion and inion and placing the electrodes at 10% or 20% intervals along the nasion-inion line. This approach avoids the problem of inaccurate event localization due to differences in head sizes. Electrodes placed over the left hemisphere are denoted with odd numbers, while the sites corresponding to the right hemisphere are designated with even numbers. Preceding the digits, the letters are subscribed to the brain area they cover: F as frontal, Fp as frontopolar, T as temporal, C as central, P as parietal, O as occipital and the earlobe electrodes are denoted by A. Midline electrodes receive a z-subscript, implying “zero”. As certain experimental and clinical environments require different electrode positions than those offered by the 10-20 system, the need arose to define a wider location system. The 10-10 system is composed by 75 electrode placements (Figure 2.11c), including the positions in between the standard locations of

Table 2.1 - Comparison of the most common neuroimaging techniques. Adapted from [61].

Technique	**Data quality**	**Temporal resolution**	**Spatial resolution**	**Volume scale**	**Safety**	**Cost**
EEG	Medium	Very high (~1ms)	Low (1 cm)	Small	High	Low
MEG	Medium	Very high (~1ms)	Low (1-2 cm)	Bulky	High	High
MRI	High	Low (~30s)	Very high (3-6 mm)	Bulky	High	High (1M$)
CT	Low	Medium (10s)	Very high (1 mm)	Bulky	Low	Low
PET	High	Low (30s-40s)	High (5 mm)	Bulky	Low	Very high (1-2M$)
SPECT	Medium	Very low	Medium (1 cm)	Bulky	Low	High (0.5-1M$)

the 10-20 system. For example, the position between F3 and F7 is called F5, the position between F3 and C3 is denoted by FC3, and so on. [62]

Even though scalp electrodes measure the summation of neuron activity, higher voltage waves do not always imply more neuronal activity, nor a flatter EEG means less activity. In fact, when the neurons present the same type of charge shift at the same time, the measuring electrode registers a net voltage change towards that direction. For example, if the neurons perform a net shift from negative to positive, the net voltage measured by the electrode will change towards positive. However, if half of the neurons make a net shift towards positive and the other half make a net shift to negative, both population of neurons cancel each other, and the result is seen by a more flattened EEG. Although the flat EEG may represent the absence of brain activity in large strokes or deep coma, a flattening of the EEG is not a sign of less activity or resting state of the brain. Higher amplitude EEG is a sign of higher synchrony between the neurons in that area. Yet, this is not the only parameter involved in variations in the amplitude of the EEG. [62]

The output of an EEG channel represents a comparison of two different points of the body, rather than an absolute measurement made at a single location. In fact, the EEG channels can be understood

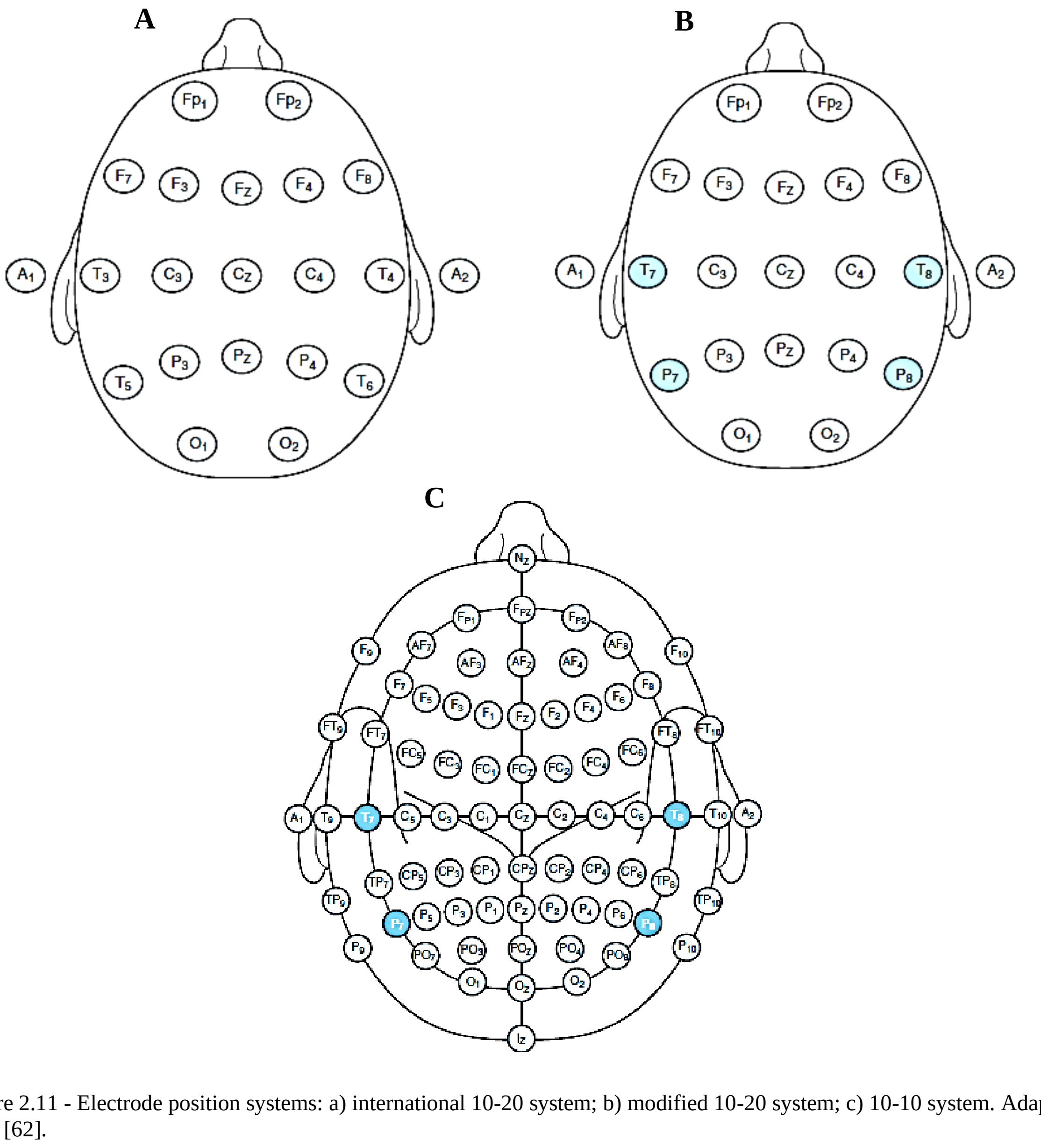

Figure 2.11 - Electrode position systems: a) international 10-20 system; b) modified 10-20 system; c) 10-10 system. Adapted from [62].

as constantly fluctuating voltmeters comparing two inputs. This is why an EEG system requires a reference electrode location. Electrical grounds should not be used as an EEG reference because they are generally not electrically neutral, due to the contamination with noise from other electrical devices connected to the same ground. Conversely, a scalp electrode does not contain only brain activity, but also a significant amount of ambient electrical noise. This electrical activity comes from the human body (forehead muscles, heart, eyes or throat) or from an indoor electrical environment that contaminates our body with the frequency of the transmission-line caused by alternate current. It is important to have these issues in consideration when defining the reference site. For example, a choice of the foot electrode as a reference would detect the same electrical noise of the body as the scalp electrode. The signals are then subtracted and the noise common to both electrodes is cancelled. The distance between the measuring and reference electrodes is also important for the characteristics of the signal: the closer is the electrode to the reference, the more attenuated the signal will appear. The reason behind this is the common brain activity captured by both electrodes that cancels out after the subtraction. Larger interelectrode distances are associated to higher amplitudes, and smaller distances are linked to smaller signal amplitudes. In overall, the ideal reference containing all of the electrical noise and none of the electrocerebral activity does not actually exist. The location of the electrode reference must be chosen taking into account the balance between the fair noise cancelation and small brain activity cancellation. [62]

Another important aspect in electroencephalography is the presence of artifacts. Artifacts are EEG waveforms that are not of neuronal origin and may contaminate the EEG in frequency or time domain. As mentioned above, these might be originated by eye movements, heartbeat, face muscles or other internal or external sources. The main EEG artifacts are explained below [62], [63].

Physiological (or internal) artifacts are originated by electrical activity of other body parts and can be summarized as follows:

- Eye movement artifacts – such can be eye blinks, high amplitude slow wave signals, artifacts from eyeball and eyelid movement, usually present at frontoparietal positions as 3Hz to 10Hz signal, or electroretinogram artifact, a potential difference between retina and cornea that changes with incident light.
- Cardiac artifact – originated by electrocardiogram and appears similar to the QRS complex within EEG. Most prominent in left temporal regions.
- Muscle artifacts – fast waves with variable amplitude depending on degree of muscle contraction. They usually affect frontal and temporal electrodes and can arise from head movement, tongue movement, chewing or swallowing.

The source of external artifacts is everything else beyond the electrical activity of the body:

- Sweat artifact – slow, wandering deviations of the channel's baseline.
- Phone artifact – mobile phone signal generates a high frequency spurious signal.
- Transmission-line artifact – small amounts of AC current (50 Hz or 60 Hz for America and parts of Asia) is present in our body, contaminating the EEG in gamma band.
- Artifacts caused by electrodes – poor contact between the electrode and the skin originates low frequency artifacts synchronized, for example, with the breathing motion; muscle movement may also cause electrode movement, generating artifacts disorganized morphology and phase reversals without consistency in polarity.

Most of the artifacts can be avoided during the recording procedure by correctly placing the electrodes in the scalp and by giving the participants instructions to avoid any kind of movement. However, it is important to detect and remove the artifacts that still remain in the EEG. This can be performed by applying artifacts rejection algorithms, by using filters or inspect and manually reject the observed artifact. These topics will be covered in “Methods” chapter.

2.3.2 Low-cost portable EEG devices

The development of EEG technology has led to expansion of this technique to the consumer market. While the cost of the conventional medical and research grade EEG systems is in the order of tens of thousands of dollars, consumer grade devices do not usually exceed $1000. The great advantage of consumer grade systems, besides the price, is their portability, flexibility and ease of use. Also referred to as mobile EEG, these systems rely on wireless technology and dry electrodes, which decrease preparation time and eliminate the need to apply conductive gel. The use of dry electrodes might also represent a disadvantage, as the conductive gel drops the impedance between the scalp and the electrode and increases the signal quality. Another disadvantage of low-cost EEG devices is low sampling rates in comparison to research-grade devices. The consequence is a decrease in time resolution, however this issue might not be critical, depending on what the studies focus on. Nevertheless, the positive factors promoted the use of mobile EEG devices in brain-computer interface (BCI) applications, such as home automation control or stress monitoring. Conversely, low-cost EEG systems offer a great opportunity for research in cognitive neuroscience and neurodevelopmental disorders [64].

In this study, Interaxon Muse headset [30] is used to obtain the EEG. This device has been utilized in research and by commercial users, as it was designed to help people to build meditation practices. Muse connects to a mobile device app via Bluetooth that monitors meditation sessions, providing a non-traditional neurofeedback where the Muse software applies a trade-secret algorithm, developed through machine learning to reward a decrease in EEG signatures of mind-wandering. Muse is constituted by 4 electrodes, measuring brain activity at positions AF7, AF8, TP9 and TP10, referenced to Fpz. The next paragraphs discuss the validation of Muse headband for scientific research, as well as studies that use this device are presented.

In a study that compares different brain monitoring devices and its ability for a scientific use [65], Muse is classified as recommended for exploratory use and supportive data, however the authors considered that more validation data and experience is needed. Muse was demonstrated to have a great potential in a study that defines a model that can be trained to classify two mental states with abstract contextual differences [66]. The authors discovered the presence of several sources of noise in Muse, such as muscle and electro-ocular artifacts, yet these effects also appeared in medical grade devices. The biggest challenges during Muse operation were salt bridges, an artifact when 2 channels contributing to the same derivation are isoelectric, and electrode popping, when a good skin contact was not achieved. Peining et al. [67] assessed the applicability of Muse for BCI drone control, obtaining an average accuracy of 70% with a support vector machine classifier. A study that compares several consumer grade electroencephalographic devices [68], reports this accuracy to be the highest among other systems. To validate Muse system for research, its performance was compared to standard research-grade Brain Vision actiCHamp and g.Tec g.USBamp systems [69]. The developers consider that Muse achieved similar performance in voltage trace, comparatively to Brain Vision actiCHamp. Conversely, Muse demonstrated similar measures in the mean normalized hemispheric power, in comparison to g.Tec

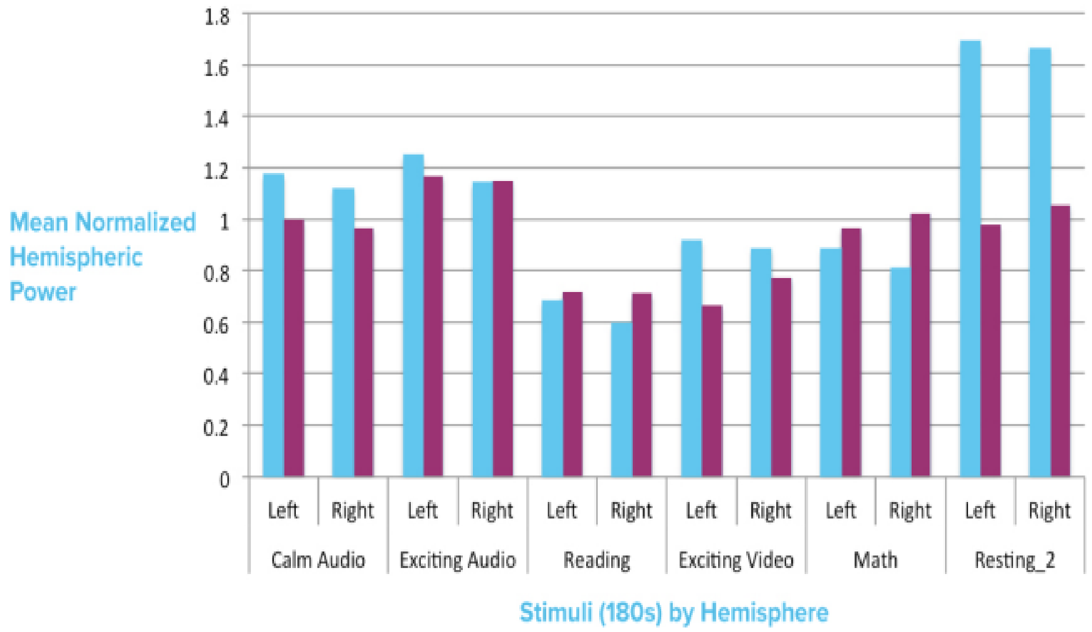

Figure 2.12 - Mean normalized hemispheric power: Muse (blue) vs g.Tec (purple). Source: [69].

g.USBamp system (Figure 2.12), during a standard set of cognitive tasks. The total power was calculated as the median variance across 180x1s epochs, across stimuli, averaged over four Muse and eight g.Tec electrode channels, and averaged across 11 participants.

Muse system was compared to Brain Vision actiCHamp in another validation study. Krigolson et al. [70] demonstrated that it is possible to conduct ERP research without being reliant on event markers, which are usually required for averaging processes. In this experiment, the participants were submitted to a visual oddball and a reward-learning tasks separated in two groups: the standard group, in which the EEG acquisition was performed using actiCHamp system; and the Muse group, where the EEG data were recorded from Muse headband using muse-io and streaming the data from Muse EEG system directly to MATLAB. The number of stimuli contained 90 control and 30 oddball stimuli. Since Muse do not offer a tool for marking events, instead of recording a continuous EEG and extracting epochs with delimited event onsets, 1000 ms of the streaming data after the onset of stimulus was sampled directly to MATLAB. The EEG samples were pre-processed and then segmented from the onset of the stimulus to 600 ms after. For each participant and event of interest, ERP waveforms were created by averaging the segmented EEG data for each electrode and a grand average waveform was created by averaging corresponding ERPs across all participants. The ERP components of interest were quantified by first identifying the time point of maximal deflection from 0 µV: N200 at 236 ms and P300 at 397 ms, showed in Figure 2.13, and reward positivity at 301 ms. Even though the ERP components do not look like they typically do and despite some lag in latency introduced by Bluetooth connection, this study shows that it is possible to quantify the ERP components in a reliable manner using Muse. Another attempt to measure ERPs with Muse system was performed by Alexandre Barachant [71], obtaining an identifiable P300 in channels TP9 and TP10. In spite of not revealing how Muse was set up to mark the events, the methodology for identifying the P300 component followed standard steps. The stimulus were presented for 200 ms at an interval of 600 ms, with a total count of 960 non-target and 184 target stimuli. Then the EEG data was pre-processed, epoched (from -100ms to 800ms after the stimulus onset) and averaged.

Several studies, beyond ERP research, were performed using the Muse headset. Hashemi et al. [72] conducted a high-density study to characterize population EEG dynamics throughout adulthood. The

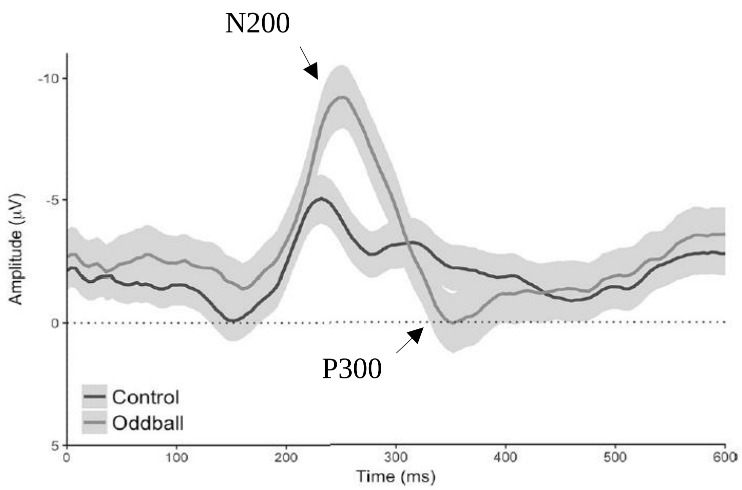

Figure 2.13 – Oddball paradigm grand average ERP waveforms, obtained from TP9 and TP10 Muse electrodes. Shaded regions reflect 95% confidence intervals around the waveform. Adapted from [63].

data were collected from Muse database, containing a total of 6081 participants who subscribed into the optional research program in the accompanying Muse/Calm mobile application. The study investigated how EEG power in the traditional frequency bands, alpha peak frequency, and alpha asymmetry changes as a function of age and sex. The results suggested an overall shift in band power from lower to higher frequencies related to age, especially prominent in females. Age-related changes depend on frequency band, showing a gradual slowing of peak alpha frequency with increasing age. The assessment of alpha asymmetry revealed higher right frontal activity. Arsalan et al. [73] proposed a new feature selection algorithm for classification of perceived mental stress measured with an EEG based method, achieving an accuracy of 92.85% and 64.28% for two- and three class stress classification respectively, while utilizing five groups of features from EEG theta band. To compare brain activity between expert surgeons and intermediate or novice surgeons during a surgical simulation, Maddox et al. [74] quantified the area under the curve of gamma and alpha EEG wave tracings as a measurement of concentration and stress levels. Experienced surgeons showed a significant increase in concentration levels and a decrease in stress levels, compared to novices. Recent research with Muse explores stress classification using EEG signals in response to music tracks [75]. Five groups of features, including absolute power, relative power, coherence, phase lag, and amplitude asymmetry, were used by four classifier algorithms for stress classification. The findings show that logistic regression performs well in identifying stress, with the highest reported accuracy of 98.76% and 95.06% for two- and three-level classification, respectively.

Overall, Muse shows to be advantageous and comparable to some standard medical grade EEG devices. Despite some operation issues, the possibility to measure ERPs, together with high accuracies of classification reported in several studies, prove that Muse can be an adequate tool for electroencephalographic research.

2.3.3 Binaural beats and brain response - EEG applications

It is known that a binaural beat is generated in superior olivary nucleus of each brain hemisphere, then migrates to reticular formation in brainstem, following to the cerebral cortex [1], where it can be measured as a frequency following response (FFR). This effect is a tendency of the electrocortical activity to alter the power and synchronize its neural activity to the same rhythm as the external stimulus [76]. Neurons are capable of discharge in some degree of synchrony with the stimulus wave form at low frequencies, however they fail to coincide within the time interval necessary for synaptic summation. In contrast, at high frequencies neurons discharge alternately and relatively few can participate in any given volley. The binaural beat appears in intermediate frequencies when two afferent streams join in a common neural centre with a relatively precise synchrony. A listener exposed to two tones with slightly different frequencies in each ear is only capable of perceiving the binaural beat if the stimuli are between 90 and 1000 Hz and differ by no more than 35 Hz [77]. The scientific community is still unsure whether the synchronization happens naturally, a mechanism denominated as neural entrainment, or whether this process is caused by an increased hemispheric connectivity between the auditory cortices, an inconsistency evidenced by the most recent meta-analysis [78]. Other studies failed to observe any synchronization of the neural activity with BB stimulus. This section presents a review of electroencephalographic studies on the effects of binaural beat stimulation and the subsequent brain responses.

The most recent study about the effect of binaural beats on brain theta activity [14] suggested that a 6 Hz on a 250 Hz carrier tone was a stimulus for inducing a meditative state and the FFR was observed. The participants underwent a 30 minutes 6 Hz BB stimulation (experimental group) or silence (control group). An EEG was recorded during this period, including a pre-stimulus baseline and post-stimulus recordings. The brain responses to the stimulus were investigated by comparing each exposure duration, comprising 5-min segments of the EEG recording. During the stimulation period, the absolute power of the theta activity was enhanced at almost all cortical positions within the first 10 minutes of stimulation (Figure 2.14). Following other periods of exposure, different cortical positions were enhanced, including frontal midline, responsible for reflecting meditative state. During the post-stimulus period, there were no differences in absolute theta activity comparing to the baseline. At all time-points, the left hemisphere presented more dominant significance than the right hemisphere. In the control group, theta brainwave enhancement was not observed. All these findings support FFR and theta neural entrainment.

Karino et al. [15] confirmed that the activity of the human cerebral cortex can be synchronized with slow binaural beats, through a magnetoencephalographic study. An auditory steady state response (ASSR) is a continuous scalp recorded potential that can be elicited by a range of stimuli, including continuous amplitude modulated and frequency modulated tones. To elicit an ASSR, the subjects were stimulated with theta 4 Hz and 6.66 Hz BBs on 240 Hz and 480 Hz carrier tones, during 5 to 10 minutes. The control condition included 240 Hz and 480 Hz pure tones. In total, averaged steady-state responses in eight types of BB conditions and two kinds of no-BB conditions were recorded for each subject. Two methods were used in the analysis of magnetic fields in each channel to search those that represent ASSR to BB in each subject. One method examined the configuration of averaged magnetic field, and the other the FFT with a specific peak at BB frequency. The results showed that most subjects presented dominant

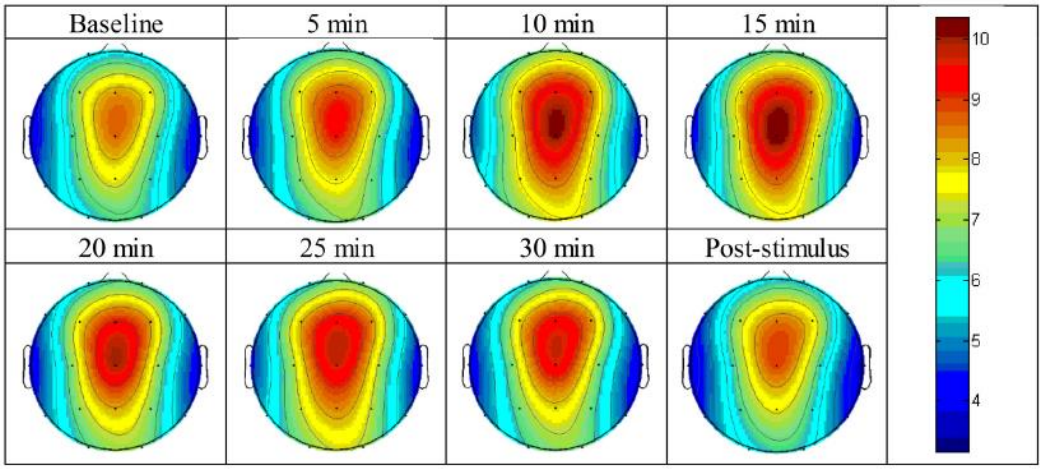

Figure 2.14 – Topographic absolute power of theta activity during pre-stimulus baseline recording, stimulation with 6 Hz binaural beats and post-stimulus recording. Replicated from [14].

activation in the left and right temporal areas, which means that the main source of ASSR to BB are auditory cortices similar to conventional ASSR. In addition, 4 Hz BB spectral component was detected in the frontal, parietal, occipital electrodes as well as in the temporal areas.

Brady and Stevens [16] observed that theta BBs induced theta EEG activity and increased hypnotic susceptibility. Six participants were categorized accordingly to their hypnotic susceptibility level as low, medium and high. The stimulus was a complex theta BB pattern, generated by a continually varying theta left-right frequency difference, presented during 20 minutes within 3 sessions. The control stimulus was produced with pink noise and the same tones as the experimental stimulus, but without binaural beats, so that the control and experimental sounds were perceptually indistinguishable. The results showed an increase in hypnotization level in low and medium groups after BB stimulation, while in the high group there were no changes. Regarding theta activity, relative power in five of six participants increased over the sessions, observed within BB condition. Four of the participants presented gradual and progressive theta-entrainment effect among 3 sessions, compared to baseline theta activity. Three years later, Stevens et al. [79] replicated the same study, using a larger scale of participants, larger time of binaural beat stimulation and a control group. Surprisingly, the results were contradictory. In spite of the increased theta activity across training, there were no significant differences between experimental group who received theta BB training, and control group who received pink noise. Most of the variability in frontal theta rhythm observed in this study was not due to the BB training. The prolonged exposure to theta BBs may have produced a “theta blocking” effect by eye opening, cognitive alerting, or attention to other stimulus, since the participants reported to be bored during 1-hour stimulations among 3 sessions. Another reason for the inconsistent results may be the difference in waveform and in amplitude from the stimulus used in the original study, even though it was in range of theta frequency. The recommendations for future work included selecting motivated participants, applying a stimulus of unimodal, high amplitude, high theta frequency range between 5.5 Hz and 7.5 Hz and a careful selection of control conditions with no interference on theta activity, as the use of pink noise in control group may have influenced theta rhythm.

Other studies failed in observing neural entrainment, however evidences of increased synchrony between the hemispheres as a response for BB perception were found. Wahbeh et al. [13] conducted a study with a 30-minute 7 Hz BB stimulation (133 Hz presented to the left ear and 140 Hz presented to the right ear), and rain sounds used as control stimulus. Fast Fourier Transform analysis was performed to extract the magnitude of brain frequencies, demonstrating that the control stimulus produced larger amount of total theta power in the control condition than the BB condition. During the binaural beat listening, only one subject had a dominant EEG frequency within theta range. To assess the relation between brain areas, coherence analysis was performed. The results revealed no difference between experimental and control conditions between anterior-posterior areas, however coherence at 7 Hz was slightly larger between left and right frontal locations during the BB stimulation. The study did not observe neural entrainment, however the findings support the hypothesis of increased interhemispheric connectivity as a response to BBs.

A study conducted by Solcà et al. [17] intended to test whether BBs synchronize activity between hemispheres, both at the neural and at the behavioural level. The experiment was divided into two parts: one that evaluated neural changes while listening to 10 Hz alpha BBs (produced from 395 Hz and 405 Hz tones), 4 Hz theta BB (produced from 398 Hz and 402 Hz tones) and corresponding acoustic beats as a control condition, during 4 minutes; other part assessed if BBs could increase binaural auditory discriminability by performing a dichotic digit task, presented before and after listening to 3 min of 10 Hz BBs and before and after listening to the corresponding AB. Regarding the first part, interhemispheric coherence between the transverse temporal gyri was significantly greater, specifically in the alpha band during 10 Hz alpha BBs stimulation, compared to the 10 Hz control condition (Figure 2.15a). A similar coherence spectrogram pattern was found during 4 Hz BBs stimulation, compared to

4 Hz control condition (Figure 2.15b). A voxel-wise analysis of interhemispheric coherence showed that this increase during the BB condition was relatively specific to the primary auditory cortex, although changes were also observed in frontal and occipital areas. Changes in oscillatory synchrony were not associated with changes in amplitude and no increase in power was observed during 10 Hz and 4 Hz BB stimulation, compared to the rest or to the corresponding AB conditions. Regarding behavioural level, no significant changes were observed. The study postulates that the effect of BBs on interhemispheric communication is restricted to the alpha band because it is the main spontaneous oscillation band and is involved in most of the interactions between cortical areas.

In order to understand the mechanism underlying the BBs and the EEG changes under BB stimulations, Gao et al. [21] employed relative power to observe brainwave oscillation, phase-locking value (PLV), to detect neural entrainment, and cross mutual information (CMI), to measure brain network connectivity. A five-minute BB stimulation with four different frequencies was used, including 1 Hz delta BB (produced from 550 Hz and 551 Hz tones), 5 Hz theta BB (produced from 550 Hz and 555 Hz tones), 10 Hz alpha BB (produced from 550Hz and 560 Hz tones) and 20 Hz beta BB (produced from 550 Hz and 570 Hz tones). Relative power analysis revealed a decrease of theta and alpha bands and an increase in beta band during delta and alpha BB stimulation. Relative power of theta band was decreased during delta, theta and beta BBs. PLV reflected frequency-specific synchronization between two neuro-electric signals: under delta, alpha and beta BBs, increased anterior–posterior connectivity in the theta band was observed. Regarding CMI, the results showed different CMI variations under different BB stimulations: within delta and alpha BB presentation, CMI reduced among right temporal, frontal and occipital cortical areas; under theta and beta BBs, CMI decreased at first and then increased. The results of the study did not support brainwave entrainment or interhemispheric synchrony, however connectivity changes were detected following the variation of relative power.

Several studies did not observe neural entrainment or any other effect that might be responsible for the perception of binaural beats. With the aim to assess if BBs affect vigilance ad cortical frequency and to find a relation with personality traits, Goodin et al. [18] measured a response at either theta (7 Hz) or beta (16 Hz) frequency bands BBs, while undertaking a zero-back vigilance task. All BB tones were 2 minutes in length, with a total of 4 minutes continued presentation while white noise baseline was presented between BB stimulation epochs. No association between BBs and personality or vigilance time differences were observed. FFT analysis did not show increases in beta or theta power during beta or theta BB stimulation, respectively. The possible explanation is that the stimulation period was not enough to elicit entrainment. Conversely, entrainment may have occurred during brief events, so a frequency over time analysis is strongly recommended in future examinations.

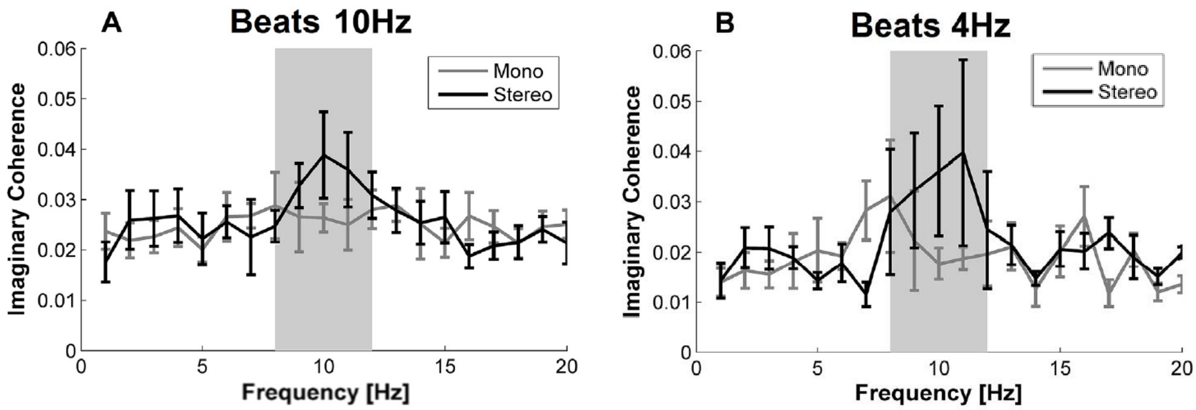

Figure 2.15 – Effect of binaural beats (stereo) on interhemispheric coherence: stimulation with a) – 10 Hz BBs and b) – 4 Hz BBs produced an increase in interhemispheric coherence between the primary auditory cortices within 9-11 Hz range of alpha rhythm, comparatively to acoustic beats (mono).

López-Caballero and Escera failed to observe EEG power enhancement as a sign of neural synchronization provoked by binaural beats [19]. The participants were presented binaurally and acoustically with different stimuli, including 4.53 Hz theta, 8.97 Hz alpha, 17.93 Hz beta, 34.49 Hz gamma and 57.3 Hz upper gamma beats, created by adding these frequency values to a tone of 372 Hz. The stimulation was performed during 3 minutes, preceded and followed by 90 seconds of pink noise, corresponding to the baseline and post-stimulus recordings, respectively. No significant changes were observed between the BB condition and the corresponding acoustic beat or the baseline. In addition, spectral EEG topographies within theta, alpha, beta, gamma and upper gamma rhythms were not affected by BBs at the respective frequency. These findings do not support the hypothesis that BBs can alter EEG spectral power.

Vernon et al. [20] did not observe an effect of binaural beat frequency eliciting a FFR. In this study, the participants were exposed to ten 1-minute epochs of different BBs. One group was stimulated with alpha BBs of 10 Hz and the second with beta BBs of 20 Hz, both on a 400 Hz carrier tone. The EEG data was obtained from the left and right temporal regions during pre-exposure baselines, stimulus exposure epochs and post-exposure baselines. No changes at either alpha or beta EEG frequencies during the exposure to BBs were observed, not supporting the effect of entrainment. Additionally, the participants that underwent alpha BB stimulation evidenced a decrease in resting baseline amplitude from the pre- to post-stimulation period. For those exposed to the beta binaural beats, there was an evidence of an increase in the beta amplitude for the left hemisphere only. The possible changes elicited by BBs may have been more prominent in other regions other than at the temporal regions, or the characteristics of BBs themselves might have influenced the results. Another hypothesis is that each frequency component of the EEG may not be equally entrained, or it must imply that participants need to attend to the stimulus for an entrainment effect to occur, that is, present any psychological or a behavioural change. Lastly, the short presentation of continuous 1-minute BB tones is either insufficient or incapable of generating changes in the EEG.

An ERP research conducted by Pratt et al. [80] did not observe differences between estimated sources of auditory evoked potentials to acoustic and binaural 3 Hz and 6 Hz beats, suggesting that the underlying cortical processing is similar. Eight different stimulus conditions were employed, including two carrier frequencies (250 Hz or 1000 Hz), two beat frequencies (3 Hz or 6 Hz) and two beat types, binaural or acoustic. The stimulus had duration of 2000 milliseconds, presented with an interstimulus period that randomly varied between 950 and 1050 milliseconds. The ERP responses showed significant differences between different stimulus conditions: acoustic beats-evoked oscillations were larger than binaural beats-evoked oscillations, and all responses were higher in amplitude with the 250 Hz compared to the 1000 Hz carrier frequency and with 3 Hz compared to 6 Hz beats. Regarding source localization, Standardized Low Resolution Electromagnetic Tomographic Analysis and Statistical non-Parametric Mapping revealed similar cortical sources during BB and AB listening. The source in all stimulus conditions was located in lateral and inferior temporal, lateralized to the left hemisphere.

Although the range of studies covering BBs is wide, it still seems to be insufficient to take solid conclusions about their effects on brain. While some studies support the hypothesis of neural entrainment and FFR process as main mechanisms responsible perception of binaural beats, further observations do not reach to the same conclusions. In spite of this failure to demonstrate neural entrainment, there is an evidence of modulating effect of BBs on brain frequencies. There are some interpretations endorsing that BBs produce higher synchrony and communication between brain hemispheres as a response to its difficult perception process. Similarly to the divergence of the effects of BBs on cognition, the discrepancy within EEG research might rely on the fact of using different stimulus and control conditions from study to study. Nevertheless, more research is needed to provide a clearer understanding of what happens in our brain upon listening to binaural beats.

3. Methods

In this chapter, the description of the material and the methodology behind the data collection, data treatment and analysis are presented. As mentioned before, this dissertation is composed by two parts with the following objectives:

- Part I - an exploratory study to perform CAEPs measurement and assess the efficiency of Muse.
- Part II – main study to assess the influence of binaural beats on episodic memory and investigate if auditory simulation with binaural beats or acoustic beats produces changes in terms of brain frequencies.

Thus, two different experiments were designed, relying on the same EEG system. To avoid redundancy, the first section of this chapter describes the EEG device used to obtain the measurements. Following, the rest of the procedures relative to each experimental design are presented.

3.1 EEG device

The EEG recording was accomplished using Muse 2016 MU-02, developed by Interaxon (Figure 3.1a) [30]. Muse obtained a CE mark, which means that this device is certified for safety according to European regulatory standards. It has four recording channels, TP9, TP10, AF7, and AF8, referenced to a fifth channel located at Fpz position (see Figure 3.1b). To measure the difference in electric potential, the signal present at the reference channel Fpz is subtracted from each of the signals at the remaining electrodes. There are two additional channels that together with the reference channel establish a driven right leg (DRL) circuit for noise suppression with 2 µV of noise floor. DLR circuits between AF7, Fpz and AF8 are used to establish that the electrodes have skin contact, after which the characteristics of the incoming EEG signal (variance, amplitude, and kurtosis) are used in a decision tree in which low power, low amplitude, and low kurtosis are favoured in classifying the real-time signal as clean [69].

The EEG data has a size of 12 bits per sample and the sampling frequency of 256 Hz. The input range is 2 mV peak-to-peak with AC coupling, acting as a high-pass filter to effectively reject the DC component that contaminates the signal. The device uses wireless connection, performed with Bluetooth Low Energy 4.0 technology. The autonomy of the headset is 10 hours, with a rechargeable lithium-ion battery. The electrodes are dry and are composed by silver at frontal positions, and conductive silicone rubber at temporal sites. The rubbery electrodes allow an easier placing and fitting of the device.

The head circumference allowed by the headset varies from 52 cm to 60 cm. The positioning of AF7 and AF8 channels may suffer a change when used on a smaller than average head: AF7 may become closer to F7 and AF8 may become closer to F8. Figure 3.1c presents the measures between the channel electrodes that can be used to determine change in electrode position based on head size. There is also a micro-USB port on the back of the earpod where an auxiliary electrode can be attached to make additional measurements.

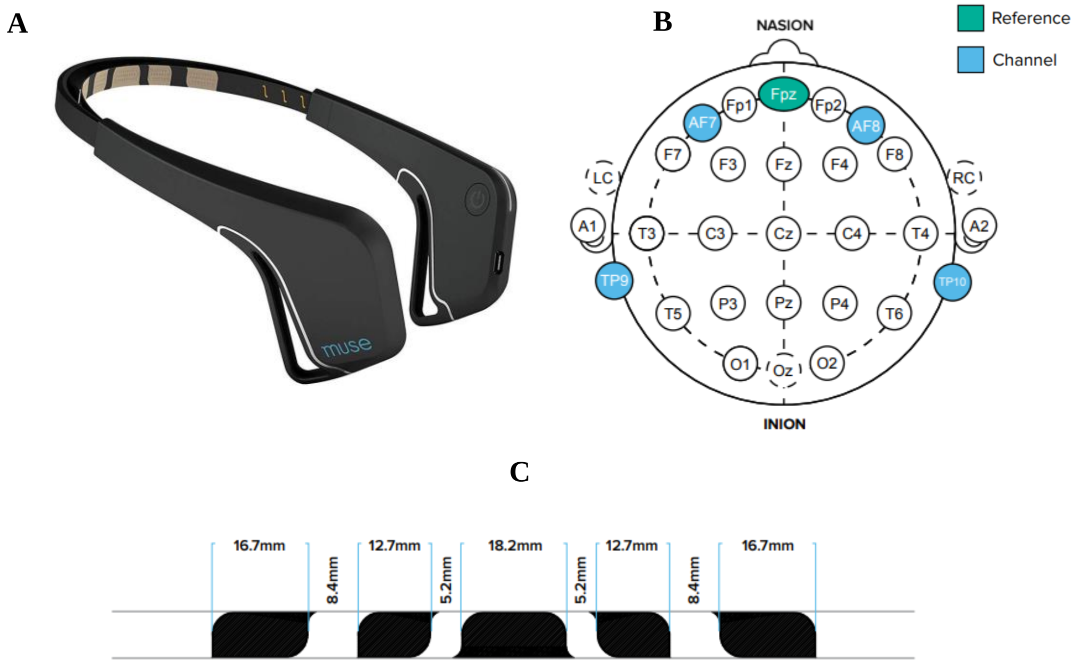

Figure 3.1 – a) Muse 2016 headset; b) Electrode locations; c) Size and distance between the frontal channels. Adapted from [69].

3.2 Part I – cortical auditory evoked potentials

3.2.1 Participants

A total of five young adults with normal hearing participated voluntarily in this study (3 male, 2 female; aged 22-25 years old). In the second, improved, attempt of the experiment, three of the previous subjects were selected for a second call for having better skin contact and, consequently, reduced noise and higher EEG signal quality (the criteria are explained later). In addition to the experiment being explained verbally, the participants were given an informative sheet where the theoretical background and all the procedures were briefly described. Thus, the volunteers were completely aware of the purpose of the study. In the beginning, the participants were informed that the experiment poses no risk to physical integrity and that they can leave at any time, without providing any justification. Written informed consent was obtained from all subjects, approved by the Ethics Committee for the Collection and Protection of Science Data of the Faculty of Sciences of the University of Lisbon.

3.2.2 Experimental procedure

As mentioned before, CAEPs are cortical responses to an auditory stimulus with specific characteristics, presented periodically. As the measurement of CAEPs is a passive task, the participants were not required to perform any assignment. The subjects were told to listen to stimulus with eyes closed, as still as possible, with tongue, mouth and facial muscles relaxed during the EEG acquisition to avoid artifacts in the signal.

The auditory stimulus was presented using ASUS Pro P2420L computer speakers, not exceeding 70 dBA, which is below the recommended exposure limit defined by The National Institute for Occupational Safety and Health (NIOSH) [81]. The environment during the experiment was calm, with an average of 35 dBA. The sound levels were measured using NIOSH Sound Level Meter App, developed by experienced acoustics engineers and hearing loss experts for researchers and occupational safety professionals [82].

CAEP are evoked by the onset from silence of an audible stimulus to stimulus offset, generally with a linear-ramped tone burst. The stimulus was produced in MATLAB, using the function *oscillator()*. The characteristics of the stimulus are the following: pure tone of a frequency of 1000 Hz, 500 ms of plateau duration, with 10 ms of rise and fall time (Figure 3.2). A rise/fall time of 10 ms at frequencies of 1 kHz and above (or 20 ms at lower frequencies) provides a good compromise between frequency specificity and response size. These characteristics follow the Recommended Procedure for Cortical Auditory Evoked Potential Testing by British Society of Audiology [83], except the plateau time of the stimulus. When using the recommended 200 ms of plateau duration, the sound was not reproduced correctly with several interruptions, due to problems in sound card of the computer. To control this problem, a longer period was chosen (500 ms) and the tone was reproduced properly. A longer plateau duration is likely to decrease the magnitude of the response [83], however this trade-off was preferable in order to provide correct presentation of the stimulus.

The number of stimuli and the interval of presentation were different at first and second attempts. Since the N1-P2 response generally takes 10 seconds to fully recover, this inter-stimulus period was chosen within the first attempt, with a total number of 30 stimuli. During the second attempt, a total of 180 stimuli were presented, with an interval of 2 seconds in between. Although reducing inter-stimulus interval might rise the problem of habituation, this adjustment was made to increase the number of stimuli, keeping the same duration of the experiment. Therefore, higher number of stimuli produce higher number of sweeps during the averaging process, increasing signal-to-noise ratio to obtain evidenced CAEP response [45].

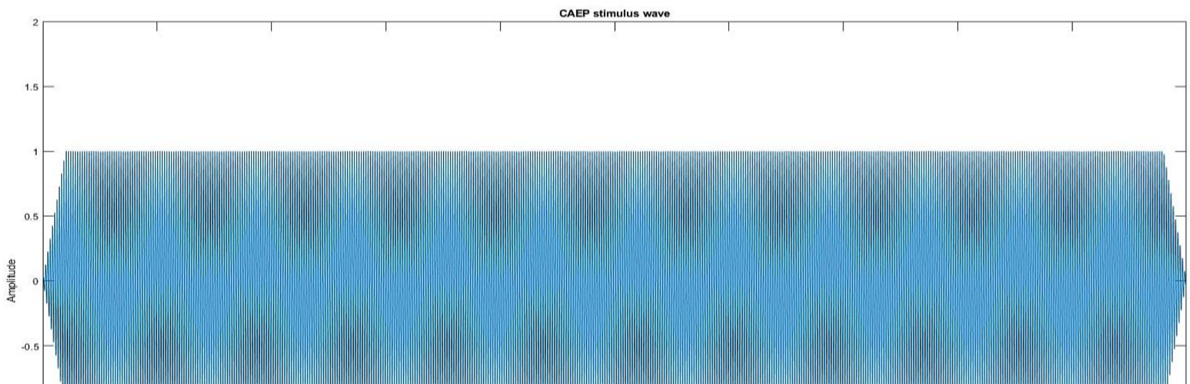

Figure 3.2 - CAEP stimulus with the frequency of 1000 Hz, plateau of 500 ms and 10 ms of rise and fall time.

3.2.3 Data acquisition

The EEG was recorded using Muse 2016 MU-02 (see Section 3.1). After the device was placed in the head, it was connected via Bluetooth to the Muse mobile app [84] to check the quality of the signal. The app provides a user-friendly interface that shows if the channels are receiving signals with good quality. If the connection is absent or weak, it is a sign that the device has not been placed correctly and that skin contact has not been reached, or that there may be interference with hair between the scalp and the electrodes.

After verifying the signal quality, the connection between the computer and the headband was established through Bluetooth using BlueMuse [85], a Windows 10 app to stream data from Muse EEG headsets via Lab Streaming Layer (LSL) libraries. LSL is a tool for a broad range of measurements of time series in research experiments that provides networking, time synchronization, near real-time access to the data as well as collection, viewing and recording of the data [86]. The stimulus presentation and the corresponding event marker stream generation to the lab network were performed using LSL libraries for MATLAB [87].

The EEG and the event marker streams were recorded using Lab Recorder App [88], a default LSL program that records all the streams on the lab network into a unique file, with time synchronization between the streams. This file comes in Extensible Data Format (XDF), a general-purpose format that was designed simultaneously with LSL to support multi-channel time series data with extensive associated meta information. MATLAB XDF importer module [89] was used to access the data from .xdf files. The schematic diagram of the data acquisition network is presented by Figure 3.3.

3.2.4 Data processing

All the steps of the EEG processing were performed using EEGLAB, an interactive MATLAB toolbox for processing continuous and event-related EEG, MEG and other electrophysiological data [90]. First, electrodes that presented excessive noise were excluded by visual inspection and by

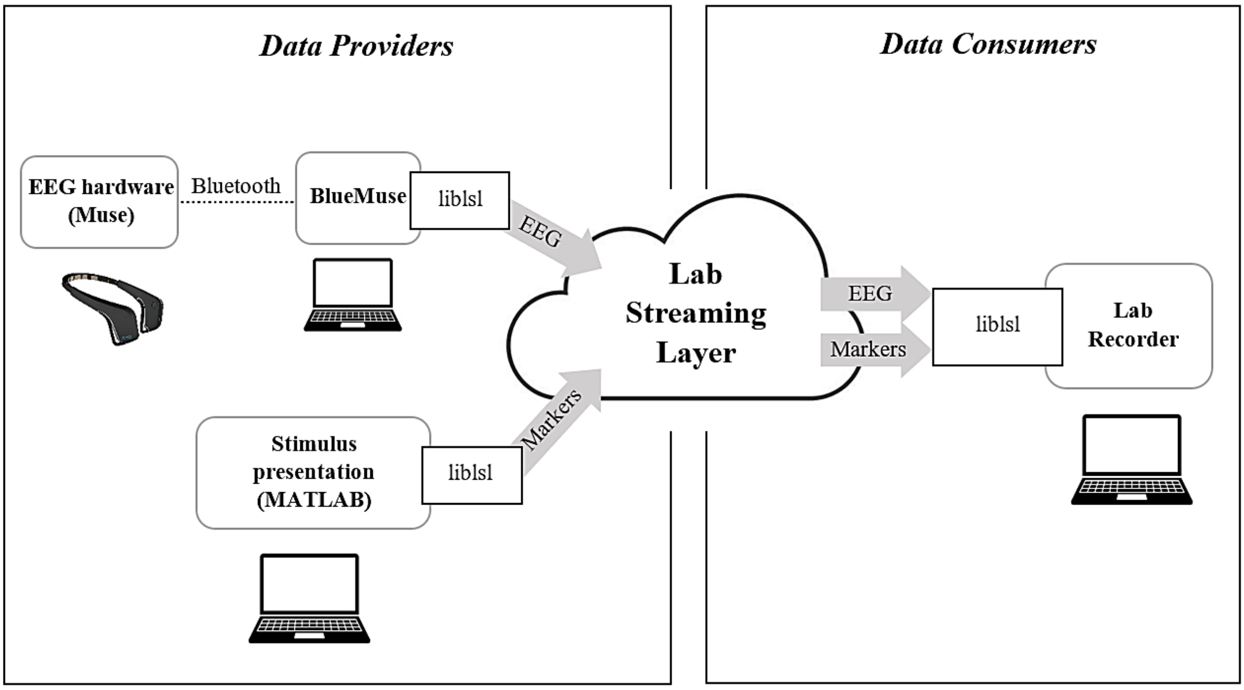

Figure 3.3 – Schematic view of the data acquisition network.

considering their spectra [91]. If one channel´s spectrum was considerably higher than the remaining channels', it was considered noisy. Following, the EEG baseline was removed and the signal was filtered using a Butterworth filter from ERPLab plugin for EEGLAB [92], with bandwidth from 1 Hz to 15 Hz and order 4. The application of a 1-15 Hz bandpass filter is effective due to the fact that the N1-P2 response has a spectral peak in the 2 to 5 Hz range [45]. The next step covered ERPLab automatic data rejection [93] containing ocular artifacts based on voltage criteria (±100 μV), with moving window of 500 ms and window step of 250 ms. Final visual inspection was made to reject segments containing the remaining artifacts. The EEG was segmented in epochs from −100 ms to 700 ms, covering the extent of the auditory long-latency response, with baseline correction of -100 ms. The epochs were averaged and the averaged ERP waveforms for each subject and channel were generated, as well as a grand average wave over all subjects.

The presence of components was evaluated by looking at local maximums or minimums in the averaged waveforms. These must be distinguishable and have an appropriate waveform morphology, latency and amplitude (see Section 2.2.3). The latency delay caused by the Bluetooth connection between Muse and computer must be taken into consideration, defined as 40 ± 20 ms by Krigolson et al. [70]. The response should be repeatable, as judged by similarity between the subjects, and have a sufficiently high signal-to-noise ratio [45].

3.3 Part II – binaural beats and episodic memory

3.3.1 Participants

A total of 32 young adults with normal hearing participated voluntarily in this study (19 male, 13 female; aged 20-28 years old). Two participants were excluded for not completing all experimental sessions. The participants received a verbal explanation of the study, as well as an informative sheet was given where the theoretical background and all the tasks were described. The volunteers were informed about the purpose of the study, however they were not told about the stimuli they would receive. The participants were assigned randomly to a beta or theta group, corresponding to the type of auditory stimulation that would be presented, beta or theta binaural beats. Before the beginning of the experiment, the participants were informed that it posed no risk to physical integrity and that they could leave at any time, without providing any justification. Written informed consent was obtained from all subjects, approved by the Ethics Committee for the Collection and Protection of Science Data of the Faculty of Sciences of the University of Lisbon.

3.3.2 Experimental procedure

As mentioned above, the participants were divided into two groups: beta (14 subjects) and theta (16 subjects). Each group participated in two consecutive weekly sessions of two blocks of tasks. In the beginning of the first block, the participants were asked to remain still and with eyes closed for 15 minutes, while each one of the groups listened to control stimuli: beta group received a 20 Hz acoustic beat and theta group listened to a 6 Hz AB. With continuous auditory stimulation, the participants were asked to view and memorize 30 images of different objects, each one with 3 seconds of duration. The images were taken from Bank of Standardized stimuli [94]. A distraction task followed, consisting in an out loud slow countdown from 20 to 0. Next, the subjects performed a 5-minute free recall test, writing down the names of the objects they remember viewing, while still listening to the stimulus. The second block started with a 15-minute presentation of the experimental stimuli to each group: beta group listened to a 20 Hz binaural beat and theta group received a 6 Hz BBs. The same memory and distraction tasks followed, except different objects were showed. The auditory stimulation persisted during the memory encoding and free recall tasks. The second session consisted of the same experimental procedure, apart from showing images with different objects in the two blocks of tasks. EEG acquisitions were taken during the first 15 minutes of each block. A workflow diagram is presented by Figure 3.4.

The stimuli were generated in MATLAB, using sinusoids with different frequencies. The 20 Hz beta BB consisted in a pure tone of 240 Hz presented to the left ear and a pure tone of 260 Hz, presented to the left ear. The 6 Hz theta BB was created from pure tones of 247 Hz and 253 Hz presented to the left and right ears, respectively. The acoustic beats were generated by summing the sinusoids of each pair of frequencies: 20 Hz beta AB resulted from the sum of 240 Hz and 260 Hz pure tones and 6 Hz theta AB was created by adding 247 Hz and 253 Hz tones. This way, both tones are presented to the left and right ears at the same time. In terms of sound, BBs and the corresponding AB counterparts are barely distinguishable. The audio was provided using sound isolating JBL T110 earphones.

This experiment was inspired on Rozengurt et al. study [29]. They observed that enhancement of theta activity by neurofeedback has influence on episodic memory, demonstrated by a strong correlation between the degree of success in theta enhancement and benefit to memory. The study consisted in three experimental groups: theta group who received theta neurofeedback training, beta group who underwent beta neurofeedback, or passive control group who watched a movie. The participants viewed 30 object pictures, each one presented for 3 seconds, followed by a free recall test that lasted approximately 5 minutes. The same test-study cycle was repeated twice more, with objects being showed in different order. Following, the participants engaged in a 30-minute neurofeedback training (or passive movie watching). Free recall tests were performed immediately after the neurofeedback session, 24h after and 1 week after. Theta group showed significantly higher performance in free recall tests, comparatively to beta and movie groups.

In our study, the division into two groups was made to replicate the study above and assess whether listening to beta or theta BBs produce differences in episodic memory performance. This hypothesis relies on the idea that BBs might produce a modulatory effect on brain frequencies, inclusive

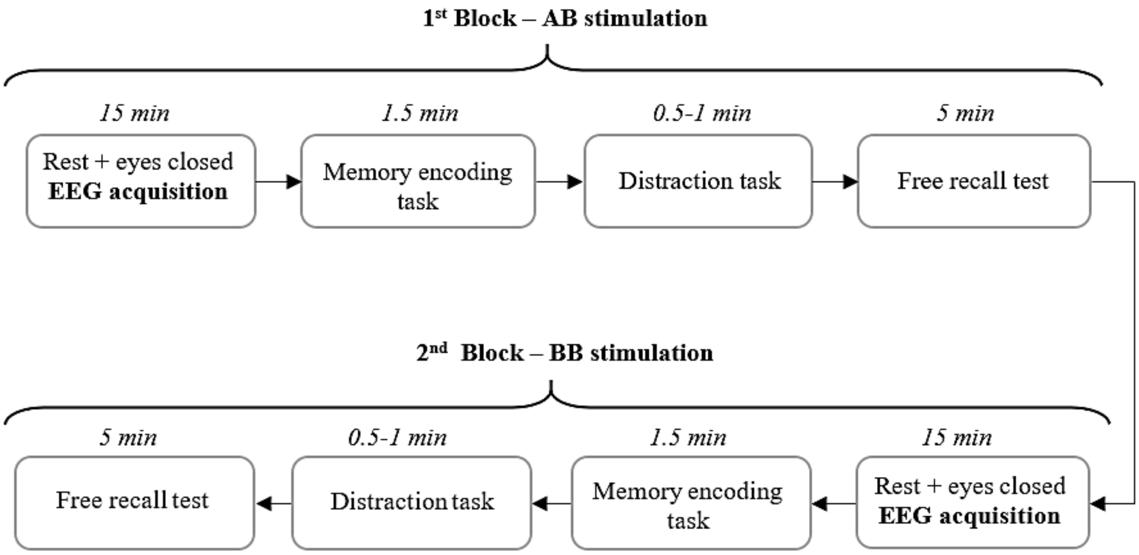

Figure 3.4 - Experimental workflow diagram, representing the set of tasks performed during the first and second sessions. Theta and beta groups received auditory stimulation with 6 Hz or 20 Hz acoustic beats (AB) during the first block, respectively; and 6 Hz or 20 Hz binaural beats (BB) during the second block, respectively.

synchronize brain activity with the frequency of the beat and elicit a FFR response. If theta activity can be enhanced by listening to theta BBs, it makes sense to presuppose that theta BB stimulation may also influence episodic memory. The presentation of control AB stimulus and experimental BB stimulus within the same group was performed to assess intra-individual differences, both in the free recall tests and in the effect in terms of brain frequencies. A 6 Hz on a 247 Hz and 253 Hz carrier tone BB was observed to produce FFR [14], which justifies the choice of these characteristics for the theta BB stimuli. A middle-range 20 Hz beta frequency was chosen for beta BB. The same study demonstrated that the effects of theta BB stimulation were present from 10 minutes. Taking this into account, the duration of BB stimulation was defined as 15 minutes. Longer periods were not considered due to participant fatigue, leading to the participants to lose interest and complete the tasks incorrectly or quicker, producing unreliable results [95].

As it was suggested that binaural-beat exposure before, and before and during the task produces superior results than exposure during the task [96], the participants listened to BBs before and during memory encoding and retrieval tasks. Since episodic memory must be immediate and must not involve rehearsal [50], a distraction task was placed between the encoding phase and the test phase of memory to prevent subjects from mentally rehearsing the objects that had been presented. The experiment included 2 sessions to further study the effect of habituation to BBs.

3.3.3 EEG acquisition

The EEG device used in this experiment is Muse 2016 MU-02 (see Section 3.1). The EEG acquisition was taken during the first 15 minutes of each experimental block. Priorly, signal quality verification was made by recording 5 seconds and inspecting the data visually in EEGLAB [90].

The acquisition frame is the same as in Part I, except the marker stream is absent in this setup (see Section 3.2.3 and Figure 3.3). Summarizing the steps, Muse was linked to the computer through Bluetooth connection, using BlueMuse application [83]. BlueMuse provided the stream of EEG data from Muse to Lab Streaming Layer [84], where it was collected and recorded by Lab Recorder App [86]. The EEG data is stored in XDF format, requiring MATLAB XDF importer module [87] to access the time-series of the EEG signal.

3.3.4 EEG pre-processing

All the steps were performed in MATLAB, version R2020b. First, the data was inspected and noisy channels were removed using automatic channel rejection algorithm from EEGLAB [97], which resorts to joint probability of the recorded channel and kurtosis values. Next, the data was uniformized by selecting the EEG from minute 1 to 14 and the DC offset was removed by subtracting the average of the signal from the signal. Assuming that the average of the varying signal component is zero over a period of time and average value of DC component is a constant, taking the average of the EEG signal extracts the value of the DC component. Subtracting it from the EEG removes the DC contribution from the signal.

A zero-phase Butterworth filter of order 8 with a bandwidth of 0.5 Hz and 50 Hz was designed using the function *designfilt()* [98], and then applied to the EEG. Butterworth is an infinite impulse response (IIR) type filter, where the output depends on all samples from the start of the data. Band-pass filtering is useful for EEG signals, as it isolates the main brain activity in delta, theta, alpha, beta and gamma frequency bands. Butterworth filter is designed to present no ripples as flat frequency response as possible, with no Ripple effect in the pass band, and zero roll off response in the stop band [99]. The frequency response of the Butterworth filter used is represented by Figure 3.5.

The data was segmented into 13 segments with the duration of 1 minute each: first segment corresponds to the interval of time from minute 1 to minute 2, second segment from minute 2 to minute 3, and so on. A second segmentation was performed by dividing each 1-minute segments into epochs with duration of 2s and 93.75% of overlap. The epoch duration and overlap values are similar to those applied in [100], a study that uses Muse to obtain the spectral characteristics of the EEG. The percentage of overlap was chosen as 93.75%, so that the number of points to overlap is a proportional integer, required by the function *buffer()* [101]. Next, an artifact rejection algorithm was computed (inspired by [70]) to mark epochs with absolute difference of more than 150 µV or gradients greater than 10 µV/ms. A criteria for exclusion of participants was set as the percentage of artifacts greater than 30% of whole EEG data, as used in [100]. The signal was reconstructed, without containing the artifacts, resulting in one full 13-minute segment of EEG data. The segmented signal was also kept to perform two types of analysis (explained further), using the full segment of EEG and using the epoched EEG.

3.3.5 Time-frequency analysis

Multiresolution Wavelet Analysis

Wavelet Transform (WT) is a useful solution to decompose non-stationary signals in time-frequency domain. While the conventional Short-Time Fourier Transform (STFT) has a constant temporal resolution for all frequencies, WT offers a superior time-frequency localization due to variable time and frequency resolutions: it provides precise frequency information at low frequencies and precise time information at high frequencies [102].

The WT decomposes a signal into a set of basis functions called wavelets. A wavelet is a smooth and brief oscillating function that can be dilated, contracted or translated from a unique mother wavelet $\Psi(t)$, defined by Equation 3.1, where $a, b \in R, a > 0$ are the scaling factor and shifting factor, respectively.

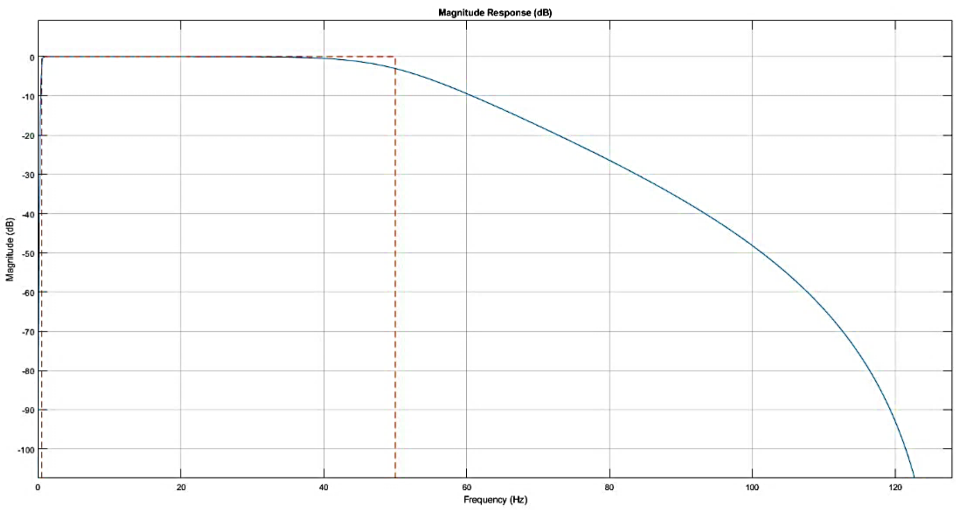

Figure 3.5 - Frequency response of Butterworth filter of 8th order and bandwidth of 0.5 Hz and 50 Hz.

$$\Psi_{a,b}(t) = |a|^{-\frac{1}{2}}\Psi\left(\frac{t-b}{a}\right) \tag{3.1}$$

The Continuous Wavelet Transform (CWT) of a signal $x(t)$ is defined as the correlation between $x(t)$ and $\Psi_{a,b}(t)$, using every possible wavelet over a range of scales and locations:

$$T(a,b) = |a|^{-\frac{1}{2}}\int_{-\infty}^{+\infty} x(t)\Psi^*\left(\frac{t-b}{a}\right)dt \tag{3.2}$$

The Discrete Wavelet Transform (DWT) is an implementation of the Wavelet Transform using a finite set of wavelet scales and translations, suitable for engineering applications. As defined by Equation 3.3, DWT performs a multiresolution decomposition of the signal by employing two types of functions, scaling function $\phi(\cdot)$ and wavelet function $\Psi(t)$, obtaining scaling coefficients c_k and the wavelet coefficients $d_{j,k}$.

$$x(t) = \sum_{k=-\infty}^{+\infty} c_k\phi(t-k) + \sum_{j=-\infty}^{+\infty}\sum_{k=-\infty}^{+\infty} d_{j,k}\Psi(2^j t - k) \tag{3.3}$$

DWT decomposes the signal into a rough approximation information, represented by first term of the right-hand side of Equation 3.3, and detail information, represented by the second term. The scaling and the wavelet functions are related to, respectively, low-pass and high-pass filters, which are applied to the signal to analyze its different frequency bands. During the multiresolution decomposition process, represented by Figure 3.6, the signal is passed through a high-pass filter $h(n)$ and a low-pass filter $g(n)$, producing two downsampled signals by a factor of 2. The output of the first high-pass filter results in a detail D1 coefficients. The output of the first low-pass filter delivers the approximation A1 signal, that is further decomposed by the second high-pass and low-pass filters, providing D2 and A2 coefficients. This process continues until the desired level of decomposition is reached. The resolution of the signal, measured by the amount of detailed information, is changed by the filtering operations, and the scale is changed by up-sampling and down-sampling operations.

The DWT decomposition was performed using the MATLAB function *wavedec()* [103], on each 2-second epoch of the segmented EEG and on the 13-minute EEG segment. The number of decomposition

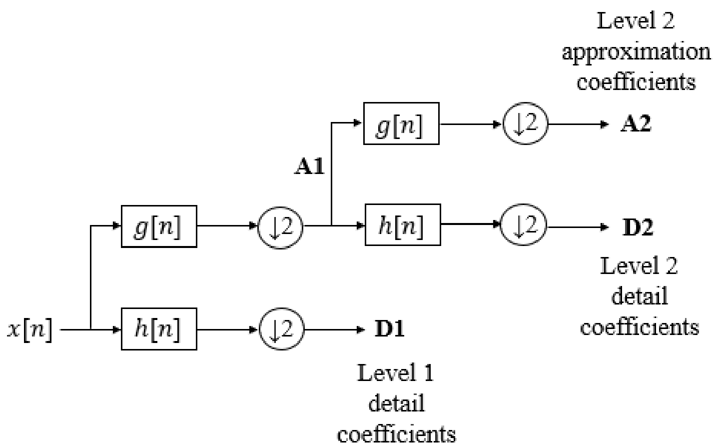

Figure 3.6 - Multilevel decomposition of DWT implementation. The signal is passed through a high-pass filter h[n] and low-pass filter g[n].

levels was selected based on the dominant frequency components of the signal. Since the EEG was pre-filtered having a bandwidth between 0.5 Hz and 50 Hz, in this analysis the number of decomposition levels was set to 4. The wavelet type Daubechies of order 4 (Figure 3.7) was chosen due to its suitable smoothing feature for detecting changes of the EEG signals [104]. The EEG signals were decomposed into D1-D4 details and a final A4 approximation, defined as decomposed signal at hypothetical level of decomposition 5, for simplification. The resulting frequency bands and corresponding designation in terms of brain rhythms of the decomposed signals for each level are listed in Table 3.1. Figure 3.8 represents an example of an EEG epoch and different decomposed signals, namely approximation A4 and details D1-D5.

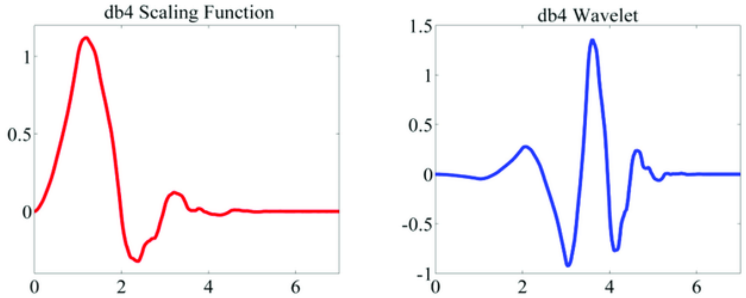

Figure 3.7 - Daubechies of order 4 scaling and wavelet functions. Adapted from [105].

Table 3.1 - Wavelet coefficients corresponding to different frequency bands, decomposition levels and brain rhythms.

Decomposed signals	Frequency bands	Rhythm	Decomposition level
D1	25-50 Hz	Gamma	1
D2	12.5-25 Hz	Beta	2
D3	6.25-12.5 Hz	Alpha	3
D4	3.125-6.25 Hz	Theta	4
A4	0-3.125 Hz	Delta	5

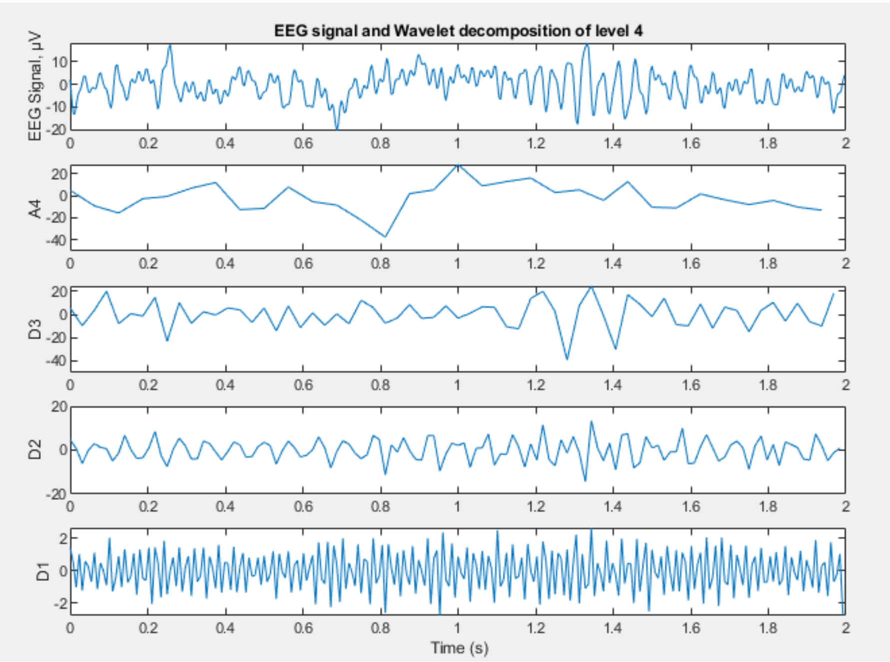

Figure 3.8 - An example of EEG epoch and corresponding decomposed signals: approximation A4 and detail D1-D3 signals.

Relative Wavelet Energy

The Relative Wavelet Energy (RWE) gives information about the relative energy associated with different frequency bands present in the EEG. Wavelet detail coefficients of all levels and approximation coefficients corresponding to the last level are used in the formulation of wavelet energy [106]. The energy at level j, out of a total of N levels, is the sum of the square of the absolute values of the detail coefficients $d_{j,k}$ and, for simplification, the energy of the approximation coefficients c_k is the energy at hypothetical decomposition level N+1. This formulation is denoted by Equations 3.4 and 3.5:

$$E_j = \sum_k |d_{j,k}|^2 \ , \qquad j = 1, \ldots, N \tag{3.4}$$

$$E_j = \sum_k |c_k|^2 \tag{3.5}$$

Total wavelet energy is calculated by summing the above defined energies:

$$E_{total} = \sum_{j=1}^{N+1} E_j \tag{3.6}$$

The RWE is defined by Equation 3.7, with $\sum_j \rho_j = 1$. This offers the information about the EEG energy distribution in frequency band of the respective level.

$$\rho_j = \frac{E_j}{E_{total}} \ , \qquad j = 1, \ldots, N + 1 \tag{3.7}$$

According to this definition, five RWE values were computed using the coefficients D1, D2, D3, D4 and A4, obtaining ρ_1, ρ_2, ρ_3, ρ_4 and ρ_5, respectively. To observe the temporal evolution of RWE, its values were computed for each 2-second EEG epoch and then averaged over the epochs, resulting in mean RWE for each one of the thirteen 1-minute segments, each level of decomposition and each channel. Alternatively, RWE was calculated for the full segment of EEG, obtaining a single value for each level of decomposition and each channel.

3.3.6 Statistical analysis

All statistical analysis was performed using R Statistical Software (version 4.0.4; R Foundation for Statistical Computing, Vienna, Austria). The R packages used were *readxl*, *tidyverse*, *ggpubr*, *rstatix*, *dplyr*, *beeswarm* and *car*. The significance level was set as $\alpha = 0.05$, with *p < 0.05, **p < 0.01 and ***p < 0.001.

Relative Wavelet Energy assessment statistics

RWE values corresponding to each one of 13 segments, as well as to the full EEG segment, 5 levels of decomposition and 4 channels were compared between the control AB condition and the experimental BB condition, within theta and beta groups, during the first and the second sessions. Initially, the RWE differences between the AB and BB conditions for each participant were computed and the *identify_outliers*() function was applied. Participants that were flagged as extreme outliers were excluded from the analysis. Next, Shapiro-Wilk normality test followed to assess the distribution of the data. If the data presented normal distribution, paired t-tests were computed. If the data did not present normal distribution, paired Wilcoxon Signed-Rank tests were applied, a non-parametric equivalent of the paired t-test. First, two-tailed tests were performed; if any statistical significance was present, one-tailed test was computed to study the directionality of the relationship.

Episodic memory and binaural beats

The number of objects recalled during the free recall test was counted and is referred to as memory score. The first step for the analysis of the data within the same group (beta or theta), differences of memory scores were computed between conditions (AB and BB) within the same session (first or second), or between sessions within the same condition. Next, an identification of outliers was made using the function *identify_outliers*() and extreme outliers were excluded from the analysis. The distribution of the differences was assessed using Shapiro-Wilk normality test. If the distribution of the data was not significantly different from normal distribution, paired t-tests were performed. Otherwise, paired Wilcoxon Signed-Rank tests were computed.

Regarding inter-group analysis, memory scores between beta and theta groups were compared within the same condition and same session. The first comprised finding and excluding extreme outliers (through *identify_outliers*() function) and Shapiro-Wilk normality test followed to assess the distribution of the samples. After, Levene's test was computed to assess the equality of variances of the scores of both groups. If the samples presented normal distribution and equal variances, independent t-tests were performed. If the samples were normal, but the variances were significantly different, the Welch Two Sample t-test was computed. If the distributions of the scores were significantly different from the normal distribution, the Wilcoxon Signed-Rank test was performed.

To assess the main and interaction effects of the group, condition and session on the scores, factorial Analysis of Variance (ANOVA) type II [107] measures were performed. It tests to demonstrate an assumed cause-effect relationship between the two or more independent variables and the dependent variable. Main effect is defined as the effect of one of the independent variables on the dependent variable, ignoring the effects of all other independent variables. A statistical interaction occurs when the effect of one independent variable on the dependent variable changes depending on the level of another independent variable. In our case, group, condition and session are categoric independent variables and memory score is a continuous dependent variable. Each one of the independent variables has two levels, namely beta and theta for group, AB and BB for condition, 1 and 2 for session. The assumptions of factorial ANOVA and their verification is presented next:

- Normality of residuals – assessed through Quantile-Quantile plot.
- Homoscedasticity – verified using Levene's test.
- Independence of observations – there is no relationship between different observations.

Episodic memory and Relative Wavelet Energy

Multiple linear regression analysis was performed to assess whether the increase in memory scores is associated to changes in RWE values, at each frequency band and channel, controlling for the session, condition and interaction between group and session. The RWE values used in this analysis are those that were obtained from the full 13-minute EEG segments. In this regression, memory score is a continuous dependent variable, RWE of each decomposition level is a continuous independent variable and session, condition and interaction between group and session are covariates that are thought to influence the dependent variable.

The model was created using the function Fitting Linear Models *lm()* and the assumptions were verified through the regression diagnostic plots:

- Residuals vs Fitted values – to verify the linearity of the data.
- Normal Quantile-Quantile plot – to check if the residuals are normally distributed.
- Spread-Location – to examine the homogeneity of variance of the residuals.
- Residuals vs Leverage – to identify influential points of the data.

4. Results

4.1 Cortical auditory evoked potentials

During the first attempt, CAEP response could not be observed. The number of 30 stimuli was insufficient to produce visible CAEP components. Moreover, several epochs were rejected for containing artifacts, leading to a total number of epochs for averaging between 15 and 20. As a consequence, a good signal-to-noise ratio was not reached and CAEP were not observed.

In a second attempt, a total of auditory 180 stimuli were presented to 3 selected subjects. This time CAEP response was observed in temporal regions, presented in Figures 4.1. Since the evoked potentials were not detected in electrodes AF7 and AF8, averages from these channels are not showed. The grand average waves were generated by averaging the ERP waveforms over all subjects for channels TP9 and TP10, represented by Figure 4.2. Overall, the N1-P2 complex was detected in all subjects, with inverted polarity, different amplitudes and varying signal-to-noise ratios. The grand average waves presented

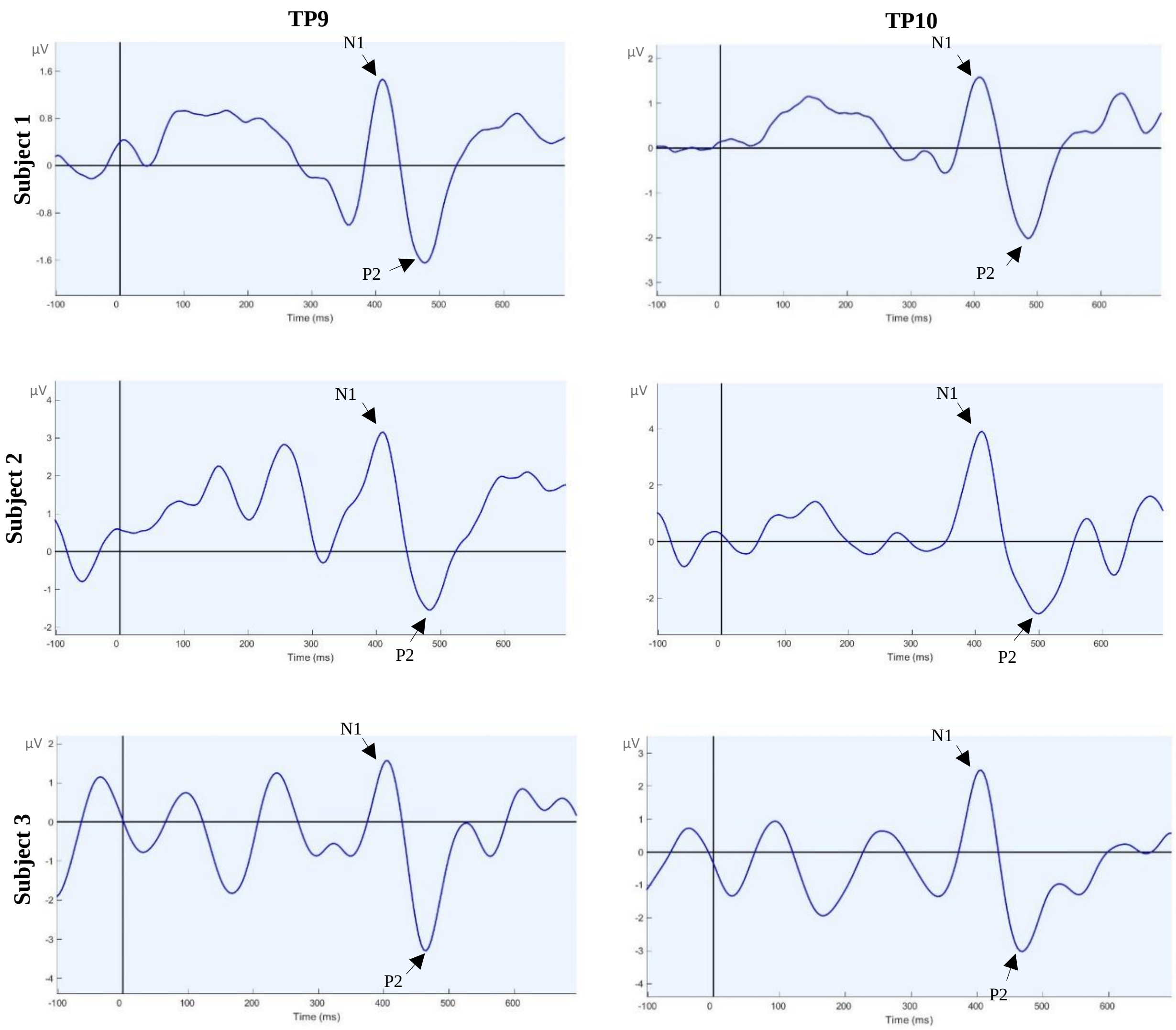

Figure 4.1 – Cortical auditory evoked potentials in channels TP9 (left column) and TP10 (right column) for each subject (rows).

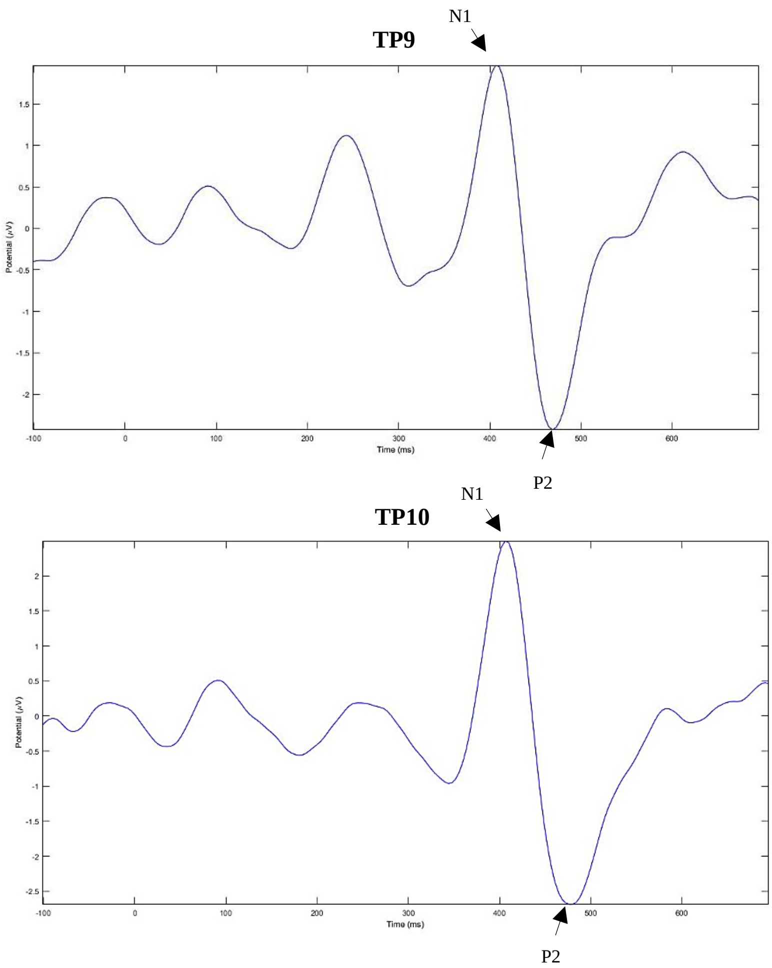

Figure 4.2 - Grand average waves over 3 subjects for channel TP9 (top) and TP10 (bottom).

discernible peaks and an acceptable signal-to-noise ratio The latency of the peaks had a constant delay around 320 ms.

4.2 Time-frequency analysis results

4.2.1 Temporal evolution of RWE

The summarized results of the paired one-tailed t-tests regarding theta and beta group are presented in Table 4.1 and Table 4.2, respectively. The red asterisks represent the statistical significance obtained from the one-tailed test, where RWE values were shown to be significantly higher during BB stimulation comparatively to AB stimulation, at specific time point, frequency band, channel and session. Similarly, blue asterisks correspond to the statistical significance of the one-tailed test where RWE during BB stimulation presented lower values than during control AB stimulation. This indicates where and when gamma, beta, alpha, theta or delta activity may have increased or decreased upon listening to binaural beats. It is important to note that the segment numbers correspond to time intervals: segment 1 is related to the interval from minute 1 to minute 2; segment 2 represents the time interval from minute 2 to minute 3; and suchlike. Full results of the two-tailed tests with statistic values, degrees of freedom and p-values can be found in Appendix A. The values of *t* and *V* correspond to parametric t-test statistic and equivalent non-parametric alternative, Wilcoxon Signed-Rank statistic, respectively.

The gamma frequency band corresponding to the D1 level was disregarded. This frequency band was still contaminated by 50 Hz of line noise. Conversely, the RWE values of the D1 level were significantly lower, comparatively to other levels ($p < 0.001$).

Table 4.1 - Statistical results obtained from t-tests for RWE between AB and BB condition for specific segment, frequency band, channel and session regarding theta group. Red and blue asterisks represent the significance of increase and decrease of RWE at corresponding frequency band, respectively. Significance: *p < 0.05. **p < 0.01. ***p < 0.001.

THETA GROUP

Session	Channel	Frequency	Time point (in minutes)												
			1	2	3	4	5	6	7	8	9	10	11	12	13
S1	TP9	Beta							* (blue)						
		Alpha	** (red)												
		Theta													
		Delta		** (red)					* (red)						
	TP10	Beta													
		Alpha													
		Theta													
		Delta													
	AF7	Beta													
		Alpha		* (red)										* (red)	
		Theta		* (red)											
		Delta													
	AF8	Beta													*** (red)
		Alpha					* (red)							** (red)	
		Theta	** (red)												
		Delta													
S2	TP9	Beta	*** (blue)												
		Alpha													
		Theta													
		Delta													
	TP10	Beta	*** (blue)	* (blue)			* (blue)								
		Alpha				* (red)	* (red)								
		Theta					** (red)	** (red)	* (red)						* (red)
		Delta	** (red)												
	AF7	Beta													
		Alpha													
		Theta					** (blue)								
		Delta													
	AF8	Beta											* (red)	
		Alpha													
		Theta													
		Delta													

Table 4.2 - Statistical results obtained from t-tests for RWE between AB and BB condition for specific segment, frequency band, channel and session regarding beta group. Red and blue asterisks represent the significance of increase and decrease of RWE at corresponding frequency band, respectively. Significance: *p < 0.05. **p < 0.01. ***p < 0.001.

BETA GROUP

Session	**Channel**	**Frequency**	**Time point (in minutes)**												
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
S1	TP9	Beta	*								*	*			**
		Alpha													
		Theta					*								
		Delta	**	**	*	*			*		*				**
	TP10	Beta	*	**		**		*	*			*			
		Alpha													
		Theta													
		Delta	**	***	**	***			*		*				
	AF7	Beta													
		Alpha													
		Theta													
		Delta	*												
	AF8	Beta													
		Alpha													
		Theta													
		Delta									*				
S2	TP9	Beta													
		Alpha													
		Theta													
		Delta	*												
	TP10	Beta													
		Alpha													
		Theta													
		Delta							*						
	AF7	Beta													
		Alpha					*								
		Theta							***	*		*			
		Delta													
	AF8	Beta													
		Alpha		*			*								
		Theta							**	*		*			
		Delta													

4.2.2 RWE with collapsed time dimension

The results of the two-sided paired t-tests are summarized in Table 4.3 (the values of *t* and *V* correspond to parametric t-test statistic and equivalent non-parametric alternative, respectively).

Regarding theta group, significant differences were observed in RWE within alpha frequency band and channel AF8 between AB (*M=0.1306, SD=0.0836)* and BB (*M=0.1584, SD=0.0973)* conditions during the first session, *t(15)=2.2701*, *p=0.03837*, more concretely RWE increased from AB to BB, *p=0.01919*. During the second session, significant differences in RWE in theta frequency band were found between AB (*M=0.1909, SD=0.1119)* and BB (*M=0.2127, SD=0.1101)* conditions in channel TP10, *t(15)=2.4509*, *p=0.02699*, with an increase of RWE from AB to BB, *p=0.0135*.

Regarding the beta group, the following observations correspond to the first session. Significant differences were observed in RWE in beta frequency band between AB (*M=0.1975, SD=0.1412)* and BB (*M=0.1394, SD=0.1027)* conditions in channel TP10, *t(13)=-2.3364*, *p=0.03613*, more specifically RWE decreased from AB to BB, *p=0.0181*. Channel TP10 also presented significant differences in RWE within delta frequency band between AB (*M=0.4809, SD=0.1867)* and BB (*M=0.5535, SD=0.1762)* conditions, *t(13)=4.3193, p=0.0008329,* with an observation of an increase from AB to BB condition, *p=0.0004164*. Moreover, significant differences in RWE within delta frequency band were detected between AB (*M=0.4704, SD=0.1773)* and BB (*M=0.5452, SD=0.1530)* conditions in channel TP9, *t(13)=2.7144*, *p=0.0177,* more specifically an increase of RWE from AB to BB, *p=0.00885*.

Table 4.3 - Results of the parametric and non-parametric paired two-sided t-tests corresponding to each group, session, channel and frequency band (level of decomposition). The t values are the test statistic of the parametric t-tests, V is the test statistic of the Ranked paired Wilcoxon Signed-Rank tests and df correspond to degrees of freedom.

Group	Session	Channel	Level of decomposition											
			D2 (13-25 Hz) Beta			D3 (6-13 Hz) Alpha			D4 (3-6 Hz) Theta			A4 (0-3 Hz) Delta		
			stat	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*
Theta	S1	TP9	t = 0.11719	15	0.9083	t = 0.51377	14	0.6154	t = -0.76229	15	0.4577	t = 0.2854	15	0.7792
		TP10	t = -0.35562	14	0.7274	t = 0.52316	15	0.6085	t = 1.2096	15	0.2452	t = -0.10778	14	0.9157
		AF7	t = 0.72671	14	0.4794	t = 1.774	15	0.09636	V = 66	15	0.9399	t = -1.8472	15	0.08454
		AF8	V = 104	15	0.0654	t = 2.2701	15	0.03837*	V = 53	15	0.4637	t = -2.0329	15	0.06016
	S2	TP9	V = 41	13	0.5016	t = 0.1466	14	0.8855	t = 0.66852	15	0.514	t = 0.45392	14	0.6568
		TP10	t = -1.758	15	0.09912	t = 1.5243	15	0.1482	t = 2.4509	15	0.02699*	t = 0.91219	15	0.3761
		AF7	V = 70	15	0.9399	t = -0.003181	15	0.9975	t = -0.90133	15	0.3817	t = -0.23786	15	0.8152
		AF8	t = -0.48405	14	0.6358	t = 0.27733	15	0.7853	t = -0.32796	15	0.7475	V = 68	15	1
Beta	S1	TP9	t = -1.956	14	0.07072	t = -0.36421	14	0.7211	t = 0.72817	14	0.4785	t = 4.3193	13	0.0008329***
		TP10	t = -2.3364	13	0.03613*	t = -0.61498	13	0.5492	t = 0.12696	13	0.9009	t = 2.7144	13	0.0177*
		AF7	t = -0.82624	12	0.7876	t = 0.65059	13	0.5266	t = 0.48264	14	0.6368	t = 1.317	14	0.209
		AF8	V = 38	14	0.2293	t = 1.3077	13	0.2136	t = 0.80885	14	0.4321	t = 0.97196	14	0.3476
	S2	TP9	t = -0.68936	11	0.5049	t = -0.86997	12	0.4014	t = 0.89164	12	0.3901	V = 37	11	0.9097
		TP10	t = 0.83041	12	0.4225	t = -0.22075	11	0.8293	t = 1.0048	12	0.3348	t = -1.0862	12	0.2987
		AF7	t = -0.64688	12	0.5299	t = 1.3323	12	0.2075	t = 0.60696	11	0.5562	t = -0.3523	12	0.7307
		AF8	t = 0.1315	12	0.8976	t = 1.1354	11	0.2803	t = 1.069	12	0.3061	V = 38	11	0.9697

4.3 Relationship between episodic memory and binaural beats

4.3.1 Intra-group analysis results

AB vs. BB

To assess whether the episodic memory performance improved after the subjects were exposed to binaural beat listening, paired t-tests were performed between AB and BB conditions, within theta and beta groups during first and second sessions.

Regarding the theta group, there was a significant difference in the scores for AB (*M=13.9, SD=3.27*) and BB (*M=14.9, SD=2.63*) conditions during first session; *t(14)=−2.48, p=0.0133*. Regarding the second session, there was also a significant difference in memory scores observed between AB (*M=13.6, SD=2.99*) and BB (*M=14.8, SD*=3.61) conditions; *t(14)=−2.67, p=0.00914* (Figure 4.3).

Performing the same analysis within beta group, significant differences in the scores were observed for AB (*M=13.0, SD=2.30*) and BB (*M=14.5, SD=1.36*) conditions during the first session, *t(14)=−2.40, p=0.0154*, and no significant differences were observed between AB (*M=16.8, SD*=1.71) and BB (*M=17.6, SD*=2.47) conditions at the second session, *t(11)=−1.56, p=0.0735*.

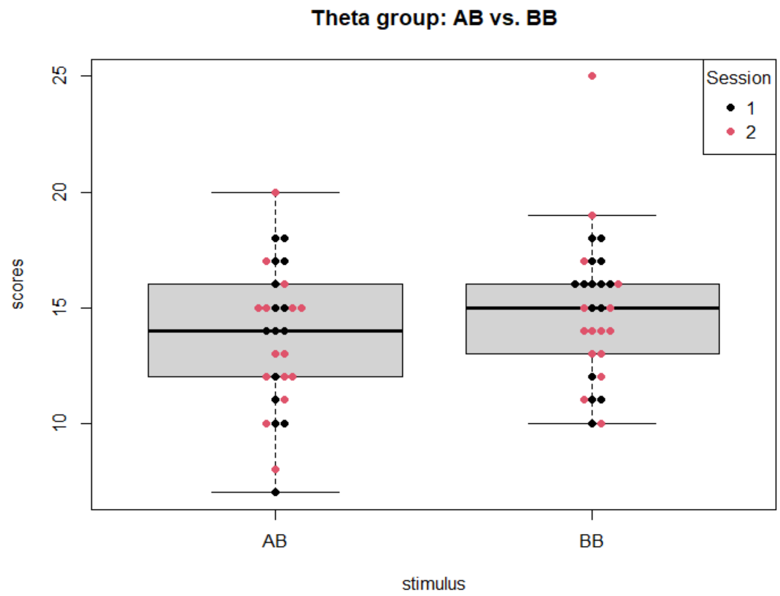

Figure 4.3 – Boxplots representing the distribution of the episodic memory scores of the theta group obtained after 15-minute auditory stimulation in each condition: AB - 6 Hz acoustic beat; BB – 6 Hz binaural beat. The black dots represent the scores obtained during the first session and the red dots correspond to the second session.

First session vs. second session

Paired t-tests were computed to compare the memory scores between the first and second sessions, within each group and condition.

Concerning the beta group, significant differences in scores were noted for first session (*M=13.0*, *SD=2.30*) and second session (*M=16.1*, *SD=2.92*) after presentation of AB stimulus, *t(12)=−3.14*, *p=0.00848*. Significant differences were also found in scores between the first session (*M=14.5*, *SD=1.36*) and second session (*M=17.4*, *SD=2.48*) after beta BB stimulation, *t(12)=−3.49*, *p=0.00445;* more precisely the scores improved, *p=0.00223*. The distribution of these data is represented in Figure 4.4.

After AB stimulation, the theta group presented no significant differences in scores between the first (*M=13.6*, *SD=3.30*) and second (*M=13.8*, *SD=2.95*) sessions; *t(15)=−0.202*, *p=0.843*. Due to the fact that the differences of the scores between the 2 sessions after BB stimulation were not distributed normally, an equivalent to non-parametric paired t-test, paired Wilcoxon Signed-Rank test, was applied to these data. Wilcoxon Signed-Rank test indicated no significant differences after theta BB presentation for the first (*Mdn=16*, *IQR=4.5*) and second (*Mdn=14*, *IQR=3.3*) sessions; *V(15)=53*, *p<0.709*. These results suggest no evidence of episodic memory improvement over sessions after theta AB and BB stimulation.

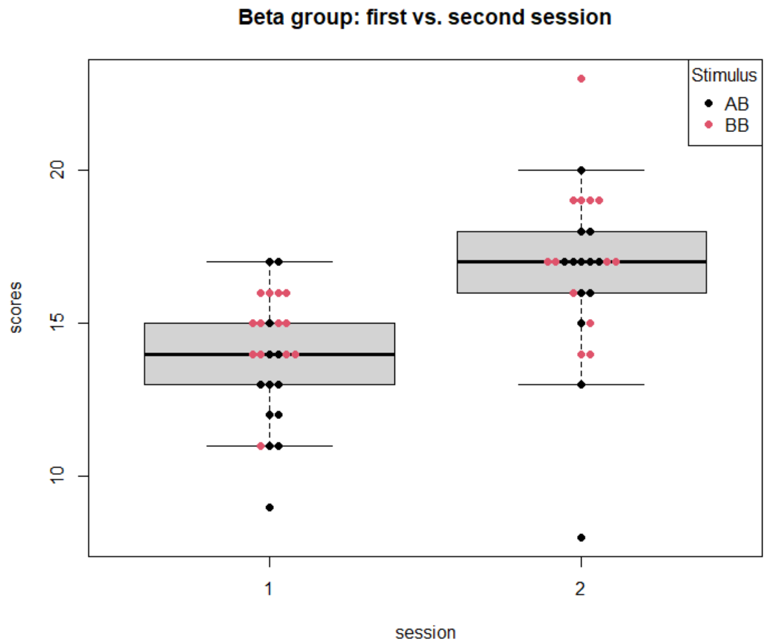

Figure 4.4 – Boxplots representing the distribution of the episodic memory scores of beta group taken at the first and second sessions. The black dots correspond to the scores obtained in AB condition – 15-minute stimulation with 20 Hz acoustic beat; and red dots correspond to the scores obtained after BB condition – 15-minute stimulation with 20 Hz binaural beat.

4.3.2 Inter-group analysis results

First session

To compare memory scores between theta and beta groups after presenting a correspondent AB stimulus within the first session, an independent t-test was computed. The results show no significant differences in scores between theta (*M=13.6, SD=3.30*) and beta (*M=13.0, SD=2.30*) groups, *t(29)=−0.607, p=0.548*. Since the data do not present normal distribution, Wilcoxon Signed-Rank test was performed to compare the memory scores between theta and beta groups after the presentation of the correspondent BB stimulus within the first session. No significant differences in memory scores were found between theta (*Mdn=16, IQR=4.5*) and beta (*Mdn=15, IQR=1.5*) groups after BB stimulation, *V(29)=95*, *p=0.324*. The interpretation is that the performance in episodic memory is similar between the theta and beta groups during the first session after receiving control and experimental stimuli.

Second session

To assess memory scores between theta and beta groups after presenting a corresponding AB stimulus within the second session, Welch Two Sample t-test was computed due to the violation of equality of variances assumption. Significant differences were detected in scores between theta (*M=13.8, SD=2.95*) and beta (*M=16.8, SD=1.71*) groups, *t(24.7)=3.37*, *p=0.00244*. An independent t-test was executed to assess the memory scores between theta and beta groups after the presentation of subsequent BB stimulus during the second session. The results presented significant differences for theta (*M=14.1, SD=2.34*) and beta (*M=17.4, SD=2.47*) groups after these received BB stimulation, *t(25)=3.58*, *p=0.00143*. These results imply that beta group presented higher episodic memory capacity than theta group during the second session, when receiving control and experimental stimulation (Figure 4.5).

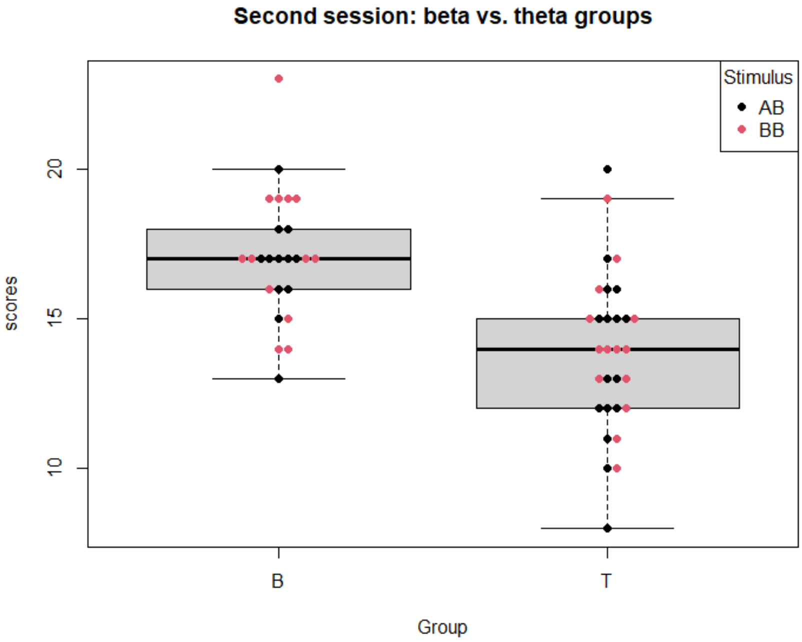

Figure 4.5 – Boxplots representing the comparison of distributions of the episodic memory scores between beta and theta groups during the second session. The black dots correspond to the scores obtained in AB condition – 15-minute stimulation with 20 Hz acoustic beat; and red dots correspond to the scores obtained after BB condition – 15-minute stimulation with 20 Hz binaural beat.

4.3.3 Main and interaction effects

A factorial ANOVA II analysis was performed to measure main effects of the independent variables on the dependent variable and the interaction effects between independent variables.

The main effect of the group on memory score was not significant, *F(1,115)=2.91, p=0.09089*, but the main effect of condition on memory score was significant, such that participants who underwent BB stimulation (*M=15.3, SD=3.18)* had higher scores than those who underwent AB stimulation (*M=14.0, SD=3.04)*, *F(1,115)=5.49*, *p=0.0208*. The main effect of the session on memory score was also significant, *F(1,115)=9.206*, *p=0.00298*, such that the scores obtained during the second session (*M=15.5, SD=3.38)* were higher than during the first session (*M=13.88, SD=2.74)*.

There was a significant interaction between groups and sessions (*F(1,115)=5.11, p=0.0256*). In the first session, the theta group obtained higher memory scores than beta group. In the second session, the beta group obtained higher scores than the theta group (Figure 4.6).

4.4 Relationship between episodic memory and RWE

The regression analysis produced a significant result in channel TP9 (*F(5,114)= 5.876, p<0.0001*), with $R^2=0.2049$. Participants' predicted memory score is equal to *12.4+3.4(D2)+1.3(CONDITION)+2.1(GROUP)(SESSION)*, where D2 denotes relative Wavelet energy at beta frequency band. The scores of the participants increased 3.4 points for each unit of RWE, 1.3 points within BB condition comparatively to AB, and 2.1 within the beta group during the second session. RWE at beta frequency band is thus a significant predictor of participants' episodic memory scores.

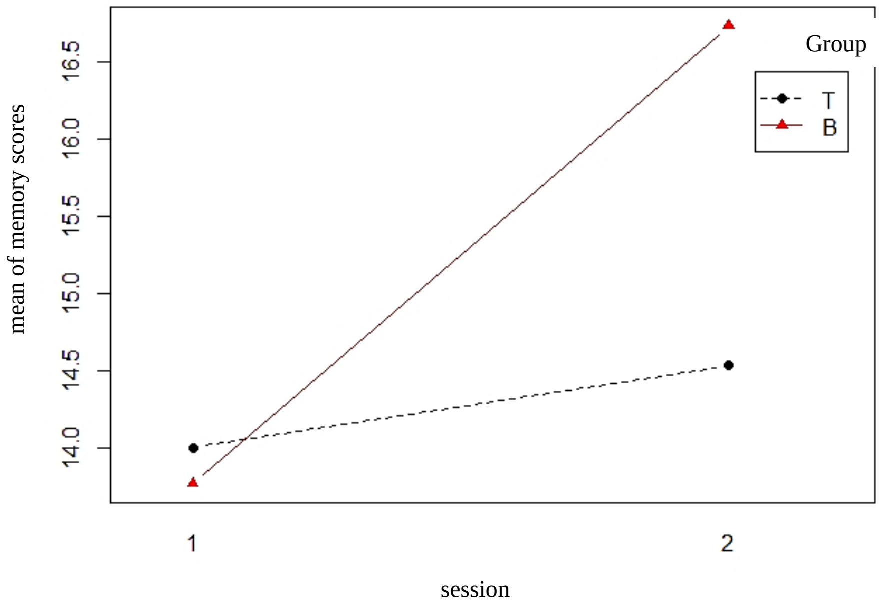

Figure 4.6 - Line graph representing the mean memory scores of the beta (B) and theta (T) groups during first and second sessions.

5. Discussion

Binaural beats are unique auditory phenomena. It is known that a dichotic presentation of two slightly differing frequencies may result in a wide array of effects on brain activity and cognition. After several years of research, it is not completely clear how exactly these sounds impact our brain. Some study lines defend that listening to BBs elicits synchronization of neural activity with the frequency of the binaural beat, a process known as entrainment. Other research found evidence that increased interhemispheric communication is a response to the demanding BB perception. And there are studies with no observations of the previously mentioned effects. The findings about the influence of BBs on cognition seem to be leading towards the same direction: positive effects were observed on working memory, long-term memory and attention capacity. However, there are no sufficient studies addressing binaural beats and episodic memory. Hereupon, the aim of this study was to investigate the effect of BBs on brain rhythms, by employing Wavelet analysis, and assess if listening to BBs can improve performance of episodic memory. This study also carries a secondary objective which was the assessment and validation of Muse for scientific research by measuring cortical auditory evoked potentials. This secondary goal was relevant in itself but also served the purpose of backing the pursuit of the main goal.

5.1 Muse validation: quantification of CAEPs

An ERP exploratory study was designed with the goal of quantifying cortical auditory evoked potentials. The results after the first attempt of the experiment did not show evidence of CAEP components. A presentation of 30 stimuli, and, as a consequence of rejection of data, even smaller number of epochs was not sufficient to achieve an acceptable signal-to-noise ratio and observable peaks. The second attempt with a higher number of stimuli, namely 180, produced quite satisfactory results: it was possible to observe N1 and P2 peaks in all tested subjects in channels TP9 and TP10 (Figure 4.1). The grand average wave presented even higher signal-to-noise ratio and more evidence of N1 and P2 components (Figure 4.2), comparatively to individual averages. There is an open question about whether the components P50 and P300 are present. Since signal-to-noise ratio is not high enough, we can only speculate about whether those are real peaks and not noise summation. No response was observed in electrodes AF7 and AF8. The reason might be the closeness of these channels to the reference FPz. Unless there is a left-right local gradient of the potential on the forehead, it is very unlikely that anything is observed in these two electrodes. The use of FPz reference is also the reason behind the inverted polarity of the N1-P2 complex. The recommended procedure [83] endorses the use of single channel recording at Cz position, with reference electrode located at mastoid. In a review paper [45], it is stated that N1 component has bilateral temporal generators beyond its frontocentral primary contribution, as well as P2 component arises from primary and secondary auditory cortices. This supports the adequacy of using temporal electrodes to measure CAEP.

An important remark is the fact that the components presented a lag of 320 ms, observed in all subjects. Despite the subject induced variability of the peak latencies, the delay is constant and not arbitrary. Krigolson et al. [70] observed a delay of 40 ± 20 ms induced by Bluetooth connection. Lab Streaming Layer guarantees that its timing errors are less than 1 ms, however points that the delays are dependent of the reliability of the device [108]. Thus, the biggest contribution to the lag is most likely originated by hardware and drivers (Muse, laptop and mouse), rather than by sending data from one server to another over the network.

Muse is a consumer-grade EEG headband that uses dry electrodes and does not rely on wiring. Its official tools only provide connection of the device to a mobile application through Bluetooth, where it is possible to record, store or share the EEG after the acquisition. Fortunately, LSL cloud-based setup offers a solution for connecting Muse and share data between any device. In addition, it provides an efficient method to mark events. Due to the presence of lag, our design can only be used to acquire data with events that can be identified by other features rather than latency of the order of milliseconds. In our case the aim was to measure CAEP components, which are recognizable by their amplitude and shape.

Nevertheless, this study shows that it is possible to quantify CAEPs in a reliable way. This method is inexpensive, offers great portability and usability and spares testing time. It does not require complex hardware and wiring to connect the electrodes, as only one laptop and wireless EEG headset were used in this paradigm. In conclusion, the Muse EEG system was validated and can be used for further investigation that does not rely on millisecond-order time locking.

5.2 Binaural beats, brain rhythms and episodic memory

With the aim of studying the influence of BBs on episodic memory and investigating if auditory simulation with BBs produces changes in terms of brain frequencies comparatively to ABs, an experiment was designed where the subjects listened to ABs (control condition) and BBs (experimental condition) during first and second block of tasks, respectively. The participants were randomly assigned to a beta or theta group, depending on the type of stimulus received: 20 Hz beta ABs and BBs; or 6 Hz theta ABs and BBs. The stimulation was performed 15 minutes before the subjects underwent the episodic memory task, while the EEG was acquired. Next, the volunteers completed a memory encoding (viewing 30 images of objects) and memory retrieval (free recall test) tasks, with a distraction in between (counting from 20 to 0). This paradigm was inspired by Rozengurt et al. [29], where an enhancement of theta activity through neurofeedback was observed and that this produced positive effect on episodic memory. Participants who received theta neurofeedback outperformed beta neurofeedback and passive control groups. As other studies also observed the involvement of theta oscillation in episodic memory processes and supposing that BBs could produce effects similar to neurofeedback, we hypothesized that upregulating theta rhythm with theta binaural beats could influence performance in episodic memory. In our case, theta and beta BB stimulation was applied instead of neurofeedback and the passive control group was replaced by adding active control AB stimulation to both groups. This was performed to study the differences between AB and BB conditions within the same individuals.

To quantify the power of brain oscillations during the BB stimulation comparatively to AB stimulation, we resorted to Discrete Wavelet Transform and Relative Wavelet Energy, with two types of analysis performed. The first one applies the DWT on each short EEG epoch of previously epoched EEG, calculates the RWE and averages across 1-minute segments, obtaining a temporal evolution of increases and decreases of RWE during 13 minutes. This division was made based on the hypothesis that the changes in brain rhythms provoked by BBs are dynamical. Jirakittayakorn and Wongsawat [14] observed changes in absolute theta power during BB stimulation at each time point with an increment of 5 minutes, during a total of 30 minutes. In our case, the division in segments of 1 minute would provide a closer look in terms of time resolution on brain frequencies. The second assessment was conducted by directly applying the DWT to the whole 13-minute segment and computing the RWE. This was performed with the expectancy of increase statistical power and to have a more general view of the changes.

The results of the first analysis revealed several increases and decreases of RWE from AB to BB condition in different intervals of time, frequency bands and channels, for both groups and sessions (Tables 4.1 and 4.2). With regard to theta group, increases of RWE in prefrontal sites were observed during the first 2 minutes at the first session. During the second session, significant increase and persistence of theta rhythm was noted from 5 minutes of BB stimulation in the right temporal lobe. This implies that a frequency following response (FFR) with the BB frequency occurred, and the entrainment of the brain activity with the frequency of the binaural beat was elicited. Concerning beta group, the FFR in beta BBs was not observed: the RWE values were significantly lower in BB condition regarding AB condition. Most significant increases were detected in delta band over temporal lobes during the first session, and in theta band over prefrontal lobes during the second session.

The findings of the second analysis are complementary to the previous results: significant increases or decreases observed in this assessment were all present at a certain time point or several time points within the previous analysis. However, some of the differences observed earlier were cancelled with the collapse of the time dimension (Table 4.3). Increase of RWE in alpha band was identified in prefrontal lobe in theta group and the idea of the FFR process is reinforced here, as the increase in theta band was still observed in the right temporal lobe. Regarding the beta group, the findings revealed a decrease in beta band and increase of delta activity in temporal lobes during the first session. The occurrence of local delta rhythm in a specific part of the brain can be related to inattention or even sleep. It is not unreasonable to think that the participants may have felt sleepy or in profound relaxation during the passive part of the experiment.

Our results are in line with Junior et al. [109], as they observed several changes in EEG spectrum between pre-stimulus and after 20 min of stimulation with 5 Hz BBs. Jirakittayakorn and Wongsawat [14] suggested dynamical brain response to BBs as different absolute powers were found at different time points. In addition, they observed synchronization of theta activity to 6 Hz BBs over whole cortex within 10 minutes of exposure. It is noted that considerably long exposure time and non-masked binaural beats appear to enhance the responses to the beats [78]. The duration of 15 minutes of BB stimulation and pure tones were chosen based on these considerations, yet our findings demonstrate FFR in theta rhythm in the beginning of the stimulation, as well as in later moments. Our results also support the dynamic process underlying theta BBs, as several changes in RWE were identified. If our study included relatively higher number of electrodes, we might have seen an increase in theta power at some different electrode locations and time points.

López-Caballero et al. [19] observed no changes in EEG spectrum after the presentation of 4.53 Hz theta 8.97 and 17.93 Hz beta BBs during 3 minutes. In our study, FFR after 1 minute was detected. Higher cortical entrainment at theta frequency elicited by 7 Hz theta AB comparatively to its binaural counterpart was observed [110], which is not in line with our results as theta energy is higher at BB condition than at equivalent AB. Wahbeh et al. [13] did not find differences between pre- and post-stimulus upon 7 Hz BB presentation, yet increases in alpha brain wave activity were observed. In our analysis, EEG changes during the presentation of BBs are detected. We also observed increases in alpha rhythm, which are associated to rest and passive mental activity, may be explained by the subjects' non-arousal state, as they were sitting relaxed and with eyes closed in a silent room. Beauchene et al. [4] showed that stimulation with 5 Hz, 10 Hz and 15 Hz BBs changes the EEG frequency responses over all channels, except no synchronization of theta activity with 5 Hz theta BBs was observed. Conversely, 15 Hz beta BBs produced higher power within the theta band, which is in agreement with our findings. A study with Parkinson's disease patients [5] reports a decrease in theta activity observed after stimulation with 14 Hz beta BBs, which once again are in line with our results.

Regarding episodic memory performance, we observed that BB stimulation increased episodic memory scores during both sessions in the theta group (Figure 4.3) and during the first session with the beta group, comparatively to the AB counterpart. It is possible that part of this improvement might be due to the order of blocks, that is, the BB block was always performed after the AB block. Westfall reports no effect of stimulation with 5 Hz theta BBs on episodic memory [25]. Comparing the memory scores between experimental sessions, the beta group obtained better results during the second session in both stimulation conditions (Figure 4.4). There is no evidence of episodic memory improvement over sessions after theta AB or BB stimulation. In addition, inter-group analysis revealed that participants who listened to beta ABs and BBs outperformed the participants that listened to theta beats (Figure 4.5).

The findings of Beauchene et al. [4] are in agreement with ours. This study observed an increase in the performance of working memory when listening to 15 Hz beta BBs. The potential explanation is that 15 Hz BB produced the highest change in the theta band frequency response magnitude, which might be applicable to our case. Since theta oscillations are strongly linked to episodic memory, upregulation of this rhythm by beta BBs may have influenced and justify the outperformance observed in beta group.

Some main and interaction effects were observed between the memory scores and the subsequent independent variables. For instance, as an effect of condition, the exposure of the participants to BBs led to higher memory performance in comparison to ABs. The same issue regarding the order of condition presentation is raised here. Session number also showed to have effect on memory, such that higher scores were obtained during the second session. An interaction between group and session was also demonstrated: group, and, consequently, type of beat (beta or theta) influences the effect of the session. Figure 4.6 shows that participants who were stimulated with beta beats had a greater improvement in memory score than participants who underwent stimulation with theta beats. Beauchene et al. [4] and one informal study [111] are in line with our results, reporting that beta BBs are associated with better results in memory tests. Observing only at the results of the t-tests, we could hypothesize that the inter-session improvement was exclusive to beta BBs, although we observed that both groups performed better during the second session. A possible explanation is that the participants were trying to achieve better results and, as a consequence, focused more on the task. Conversely, this can also be described as habituation or training, achieved during the first time of the experiment.

Linear regression analysis showed that improvements in memory score are linked to increases in RWE in beta frequency band. The idea of association between theta activity and improvements in episodic memory [27]–[29] is not supported by this outcome. Yet, the results are in conformity with other literature, as beta oscillations were observed during episodic memory retrieval process [112].

In overview, 6 Hz theta and 20 Hz beta binaural beats were showed to have a positive effect on episodic memory performance, comparatively to the respective acoustic beats. The fact that part of this effect might be due to the experiment needs to be taken into consideration. The participants who listened to beta BBs outperformed the participants that were exposed to theta BBs, which can be explained by the arousal of theta activity, observed during stimulation with beta BBs. Conversely, regression analysis revealed that increases in episodic memory scores are explained by increases in beta rhythm. Synchronization of brain activity with theta BBs was observed during the first brief moments of BB exposure, however FFR to beta BBs was absent. Apart from the statements above, our study concludes that binaural beats have a modulatory effect on brain, with involvement of dynamical responses.

5.3 Limitations and future work

One of the main limitations of this study is the number of participants. Although 32 volunteers were recruited, 2 were excluded and a division into two groups was done, reducing the size of the sample to less than half. The larger the sample size, the more accurate are the results. Larger number of subjects would have increased the statistical power. The same issue applies to the CAEP experiment: better signal-to-noise ratio would have been achieved if we had more subjects to perform the grand average. However, that would be more time-consuming and our main focus was on the second part of this dissertation. Moreover, acquisition took place during the COVID-19 pandemic, which severely constrained lab access and the mobility of potential volunteers.

The biggest constraint regarding the CAEP paradigm is the inability to observe the latency of the components due to the delay. Although this lag seemed to be constant in all individuals, we do not know if this is completely accurate. Interindividual variability of the peak's latencies together with some possible heterogeneities within the delay could have created the illusion that it is constant. Again, the sample size is too small to make solid conclusions. Although it is not possible to infer about the latencies of the components, they were observed in this study.

Another constraint of this research is the use of the EEG device with small number of electrodes. In addition, the close location of the reference FPz to AF7 and AF8 cancelled a big part of physiological information. These channels could be re-referenced, for example, to the sum of the signals of TP9 and TP10, or an auxiliary electrode could have been used to set the reference at any site. Nevertheless, resorting to an EEG system with more electrodes would have been beneficial for this study to observe brain responses to BBs in different locations.

Regarding the experiment with BBs, the stimulus was initiated some seconds after the EEG recording was started, corresponding to the time it takes to switch to MATLAB and run the script. Some subjects opened their eyes briefly to confirm whether the acquisition was taking place, instead of concentrating on the sounds from the moment they were warned the recording had started. Conversely, despite the stimulus being programmed to play for exactly 15 minutes, the acquisition was stopped manually when the script ended running. The consequence is that the duration of the EEG signals was not the same over the participants. To solve this heterogeneity, an uniformization of the data was done by removing the first minute and the extent from minute 14 until the end of the recording, getting a segment with a total duration of 13 minutes. To solve this issue, event markers for the onset and offset of the stimulation should be used in the future.

A mistake in EEG filtering was detected when the time-frequency analysis was already completed: the choice of the bandwidth between 0.5 Hz and 50 Hz did not cover the contamination of the signal from the line noise completely. The line noise represents random fluctuation of electrical impulses generated by the AC current, which corresponds to 50 Hz in Europe. A 50 Hz Notch filter should have been applied. To overcome this problem, level D1, corresponding to gamma 25-50 Hz band, had to be discarded. Fortunately, this did not bring a big loss to the data, as this frequency band was not meaningful to the results. The RWE values were significantly lower comparatively to the other levels. The same procedure was done by Guo et al. [106].

As mentioned before, we observed that listening to theta BBs produced higher episodic memory scores, comparatively to AB counterpart. This could be a result of the stimulus presentation order. A randomization of task blocks should be done in future. Conversely, EEG acquisition of the resting baseline was not performed, because it would add a further block to a paradigm which was already quite long, bringing the risk of subject fatigue. This entails the complication of not knowing what the subject's resting-state brain activity is. All the comparisons were done with respect to the stimulation with acoustic beats, and these sounds could have had their own effect on brain activity.

Although the entire procedure has been explained previously, some of the subjects seemed disoriented during the first session of the experiment in between the tasks, what may have negatively affected the focus during the first moments of stimulation and during the memory tasks This was not observed during the second session, as the participants were already familiar with the steps of the procedure. This justifies an inclusion of a training session that would have put the participants more comfortable and pay more attention to the tasks. Furthermore, the distraction task may have been too simple: counting from 20 to 0 can be quite automatic. A more elaborated interference could have been chosen to avoid any possibility of rehearsal.

Future work regarding CAEPs would be to focus in identifying the small-amplitude components P50 and P300. This can be achieved by increasing the number of subjects in the experiment, as stated above. A method to quantify the delay generated by hardware should be applied. To investigate any further effects of binaural beats on episodic memory, different frequencies and carrier tones can be applied in future studies. Other episodic memory paradigms should be performed, to test different components of this type of memory (e.g. What Where When, Unexpected Question and Source Memory tests). A longitudinal study would be advantageous to explore the long-term effects of BBs and assess its therapeutic potentials.

6. Conclusion

All goals of this dissertation were accomplished. The investigation of the potential of Muse was performed by setting a classic auditory event-related paradigm. Subsequently, an experiment was designed to assess the brain frequency response to binaural beats and their influence on episodic memory.

This study shows that the quantification of cortical auditory evoked-potentials using consumer-grade EEG system is possible. A discernible N1-P2 complex was detected.

It is demonstrated that 6 Hz theta and 20 Hz beta binaural beats have a positive effect on episodic memory performance, comparatively to the respective acoustic beats. Yet, we believe that part of this result may be due to the experiment. The participants who listened to beta BBs outperformed the participants that were exposed to theta BBs, which can be explained by the arousal of theta activity observed during beta BB stimulation. Conversely, the regression analysis revealed that increases in episodic memory scores are explained by increases in beta rhythm. Entrainment was observed within theta BB exposure, however this was not observed in beta BB stimulation.

This study provides further evidence that supports the feasibility of neuroscientific research without relying on sophisticated and expensive EEG systems. The availability of low-cost EEG devices and the development of cloud-based strategies facilitate the access and conduction of studies that normally would require high investments. Our study demonstrates that binaural beats are potential neural modulators, with involvement of dynamical responses. We observed that episodic memory is influenced by binaural beats, which can be justified by their modulatory effect on brain activity.

7. References

[1] G. Oster, “Auditory beats in the brain.,” *Sci. Am.*, vol. 229, no. 3, pp. 94-102, 1973, doi: 10.1038/scientificamerican1073-94.

[2] J. Kraus and M. Porubanová, “The effect of binaural beats on working memory capacity,” *Stud. Psychol. (Bratisl).*, vol. 57, no. 2, pp. 135-145, 2015, doi: 10.21909/sp.2015.02.689.

[3] C. Beauchene, N. Abaid, R. Moran, R. A. Diana, and A. Leonessa, “The effect of binaural beats on visuospatial working memory and cortical connectivity,” *PLoS One*, vol. 11, no. 11, p. e0166630, 2016, doi: 10.1371/journal.pone.0166630.

[4] C. Beauchene, N. Abaid, R. Moran, R. Diana, and A. Leonessa, “The effect of binaural beats on verbal working memory and cortical connectivity,” *J. Neural Eng.*, vol. 14, p. e026014, 2017, doi: 10.1088/1741-2552/aa5d67.

[5] G. Gálvez, M. Recuero, L. Canuet, and F. Del-Pozo, “Short-Term Effects of Binaural Beats on EEG Power, Functional Connectivity, Cognition, Gait and Anxiety in Parkinson’s Disease,” *Int. J. Neural Syst.*, vol. 28, no. 5, p. 1750055, 2018, doi: 10.1142/S0129065717500551.

[6] T. Ortiz *et al.*, “Impact of auditory stimulation at a frequency of 5 Hz in verbal memory,” *Actas Esp. Psiquiatr.*, vol. 36, no. 6, pp. 307-313 2008.

[7] M. Garcia-Argibay, M. Santed, and J. Reales, “Binaural auditory beats affect long-term memory,” *Psychol. Res.*, vol. 83, no. 6, pp. 1124-1136, 2017, doi: 10.1007/s00426-017-0959-2.

[8] B. Hommel, R. Sellaro, R. Fischer, S. Borg, and L. S. Colzato, “High-Frequency Binaural Beats Increase Cognitive Flexibility: Evidence from Dual-Task Crosstalk,” *Front. Psychol.*, vol. 7, p. 1287, 2016, doi: 10.3389/fpsyg.2016.01287.

[9] L. S. Colzato, H. Barone, R. Sellaro, and B. Hommel, “More attentional focusing through binaural beats: evidence from the global–local task,” *Psychol. Res.*, vol. 81, no. 1, pp. 271-277, 2017, doi: 10.1007/s00426-015-0727-0.

[10] B. K. Isik, A. Esen, B. Büyükerkmen, A. Kilinç, and D. Menziletoglu, “Effectiveness of binaural beats in reducing preoperative dental anxiety,” *Br. J. Oral Maxillofac. Surg.*, vol. 55, no. 6, pp. 571-574, 2017, doi: 10.1016/j.bjoms.2017.02.014.

[11] P. A. McConnell, B. Froeliger, E. L. Garland, J. C. Ives, and G. A. Sforzo, “Auditory driving of the autonomic nervous system: Listening to theta-frequency binaural beats post-exercise increases parasympathetic activation and sympathetic withdrawal.,” *Front. Psychol.*, vol. 5, p. 1248, 2014, doi: 10.3389/fpsyg.2014.01248.

[12] A. Crespo, M. Recuero, G. Gálvez, and A. Begoña, “Effect of Binaural Stimulation on Attention and EEG,” *Arch. Acoust.*, vol. 38, no. 4, pp. 517–528, 2013, doi: 10.2478/aoa-2013-0061.

[13] H. Wahbeh, C. Calabrese, H. Zwickey, and D. Zajdel, “Binaural beat technology in humans: A pilot study to assess neuropsychologic, physiologic, and electroencephalographic effects,” *J. Altern. Complement. Med.*, vol. 13, no. 2, pp. 199-206, 2007, doi: 10.1089/acm.2006.6201.

[14] N. Jirakittayakorn and Y. Wongsawat, “Brain responses to a 6-Hz binaural beat: Effects on general theta rhythm and frontal midline theta activity,” *Front. Neurosci.*, vol. 11, p. 365, 2017, doi: 10.3389/fnins.2017.00365.

[15] S. Karino *et al.*, “Neuromagnetic responses to binaural beat in human cerebral cortex,” *J. Neurophysiol.*, vol. 96, no. 4, pp. 1927-1938, 2006, doi: 10.1152/jn.00859.2005.

[16] B. Brady and L. Stevens, “Binaural-Beat Induced Theta EEG Activity and Hypnotic Susceptibility,” *Am. J. Clin. Hypn.*, vol. 43, no. 1, pp. 53–69, 2000, doi: 10.1080/00029157.2000.10404255.

[17] M. Solcà, A. Mottaz, and A. G. Guggisberg, “Binaural beats increase interhemispheric alpha-band coherence between auditory cortices,” *Hear. Res.*, vol. 332, pp. 233-237, 2016, doi: 10.1016/j.heares.2015.09.011.

[18] P. Goodin, J. Ciorciari, K. Baker, A. M. Carrey, M. Harper, and J. Kaufman, “A high-density eeg investigation into steady state binaural beat stimulation,” *PLoS One*, vol. 7, no. 4, p. e34789, 2012, doi: 10.1371/journal.pone.0034789.

[19] F. López-Caballero and C. Escera, “Binaural beat: A failure to enhance EEG power and

emotional arousal," *Front. Hum. Neurosci.*, vol. 11, p. 557, 2017, doi: 10.3389/fnhum.2017.00557.

[20] D. Vernon, G. Peryer, J. Louch, and M. Shaw, "Tracking EEG changes in response to alpha and beta binaural beats," *Int. J. Psychophysiol.*, vol. 93, no. 1, pp. 134-139, 2014, doi: 10.1016/j.ijpsycho.2012.10.008.

[21] X. Gao, H. Cao, D. Ming, H. Qi, X. Wang, X. Wang, R. Chen, and P. Zhou, "Analysis of EEG activity in response to binaural beats with different frequencies," *Int. J. Psychophysiol.*, vol. 94, no. 3, pp. 399–406, 2014, doi: 10.1016/j.ijpsycho.2014.10.010.

[22] L. Stevens, Z. Haga, B. Queen, B. Brady, D. Adams, J. Gilbert, E. Vaughan, C. Leach, P. Nockels, and P. McManus, "Binaural Beat Induced Theta EEG Activity and Hypnotic Susceptibility: Contradictory Results and Technical Considerations," *Am. J. Clin. Hypn.*, vol. 45, no. 4, pp. 295–309, 2003, doi: 10.1080/00029157.2003.10403543.

[23] E. Tulving, "Origin of autonoesis in episodic memory.," in *The nature of remembering: Essays in honor of Robert G. Crowder.*, Washington, DC, US: American Psychological Association, pp. 17-34, 2001, doi: 10.1037/10394-002.

[24] L. Colzato, L. Steenbergen, and R. Sellaro, "The effect of gamma-enhancing binaural beats on the control of feature bindings," *Exp. Brain Res.*, vol. 235, pp. 1–7, 2017, doi: 10.1007/s00221-017-4957-9.

[25] H. A. Westfall, "The Effect of Visual Search and Audio-Visual Entrainment on Episodic Memory," *Grad. Theses Diss.*, 2013, https://scholarcommons.usf.edu/etd/4611.

[26] W. Klimesch, M. Doppelmayr, H. Russegger, and T. Pachinger, "Theta band power in the human scalp EEG and the encoding of new information," *Neuroreport*, vol. 7, no. 7, pp. 1235-1240, 1996, doi:10.1097/00001756-199605170-00002.

[27] N. Sato and Y. Yamaguchi, "Theta synchronization networks emerge during human object–place memory encoding," *Neuroreport*, vol. 18, no. 5, pp. 419-424, 2007, doi:10.1097/WNR.0b013e3280586760.

[28] T. Staudigl and S. Hanslmayr, "Theta Oscillations at Encoding Mediate the Context-Dependent Nature of Human Episodic Memory," *Curr. Biol.*, vol. 23, no. 12, pp. 1101–1106, 2013, doi: 10.1016/j.cub.2013.04.074.

[29] R. Rozengurt, L. Shtoots, A. Sheriff, O. Sadka, and D. A. Levy, "Enhancing early consolidation of human episodic memory by theta EEG neurofeedback," *Neurobiol. Learn. Mem.*, vol. 145, pp. 165-171, 2017, doi: 10.1016/j.nlm.2017.10.005.

[30] "Muse^{TM} - Meditation Made Easy with the Muse Headband." https://choosemuse.com/ (accessed Nov. 14, 2019).

[31] C. S. von Bartheld, J. Bahney, and S. Herculano-Houzel, "The search for true numbers of neurons and glial cells in the human brain: A review of 150 years of cell counting," *J. Comp. Neurol.*, vol. 524, no. 18, pp. 3865–3895, 2016, doi: 10.1002/cne.24040.

[32] K. S. Saladin, *Human Anatomy*, McGraw-Hill, 2011.

[33] S. Ackerman, "Major Structures and Functions of the Brain," in *Discovering the Brain*, Washington (DC): National Academies Press (US), 1992.

[34] D. S. Bassett and E. T. Bullmore, "Human brain networks in health and disease," *Current Opinion in Neurology*, vol. 22, no. 4, pp. 340-347, 2009, doi: 10.1097/WCO.0b013e32832d93dd.

[35] P. A. Abhang, B. W. Gawali, and S. C. Mehrotra, "Technological Basics of EEG Recording and Operation of Apparatus," in *Introd. to EEG- Speech-Based Emot. Recognit.*, pp. 19–50, 2016, doi: 10.1016/B978-0-12-804490-2.00002-6.

[36] H. Berger, "Über das Elektrenkephalogramm des Menschen," *Arch. Psychiatr. Nervenkr.*, vol. 87, no. 1, pp. 527–570, 1929, doi: 10.1007/BF01797193.

[37] J. D. Kropotov, "Chapter 2 - Alpha Rhythms," in *Event-Related Potentials and Neurotherapy*, Ed. San Diego: Academic Press, pp. 29–58, 2009, doi: 10.1016/B978-0-12-374512-5.00002-5.

[38] P. A. Abhang, B. W. Gawali, and S. C. Mehrotra, "Chapter 3 - Technical Aspects of Brain Rhythms and Speech Parameters," in *Introduction to EEG- and Speech-Based Emotion Recognition*, Eds. Academic Press, pp. 51–79, 2016, doi: 10.1016/B978-0-12-804490-2.00003-8.

[39] J. D. Kropotov, "Chapter 3 - Beta Rhythms," in *Event-Related Potentials and Neurotherapy*,

Ed. San Diego: Academic Press, pp. 59–76, 2009, doi: 10.1016/B978-0-12-374512-5.00003-7.
[40] J. D. Kropotov, “Chapter 2.3 - Beta and Gamma Rhythms,” in *Functional neuromarkers for psychiatry: Applications for diagnosis and treatmen*t, Ed. San Diego: Academic Press, pp. 107–119, 2016, doi: 10.1016/B978-0-12-410513-3.00009-7.
[41] J. D. Kropotov, “Chapter 2.4 - Frontal Midline Theta Rhythm,” in *Functional neuromarkers for psychiatry: Applications for diagnosis and treatmen*t, Ed. San Diego: Academic Press, pp. 121–133, 2016, doi: 10.1016/B978-0-12-410513-3.00010-3.
[42] E. J. Fine, “Berger, Hans,” in *Encyclopedia of the Neurological Sciences*, Elsevier Inc., p. 411, 2014, doi: 10.1016/B978-0-12-385157-4.00827-7.
[43] M. J. Aminoff, “Chapter 3 - Electroencephalography: General Principles and Clinical Applications,” in *Aminoff's Electrodiagnosis in Clinical Neurology (Sixth Edition)*, pp. 37–84, 2012, doi: 10.1016/B978-1-4557-0308-1.00003-0.
[44] S. J. Luck, *An Introduction to the Event-Related Potential Technique, second edition*., 2014.
[45] G. Lightfoot, “Summary of the N1-P2 Cortical Auditory Evoked Potential to Estimate the Auditory Threshold in Adults,” *Semin. Hear.*, vol. 37, no. 1, pp. 1-8, 2016, doi: 10.1055/s-0035-1570334.
[46] S. J. Luck, G. F. Woodman, and E. K. Vogel, “Event-related potential studies of attention,” *Trends in Cognitive Sciences*, vol. 4, no. 11, pp. 432–440, 2000, doi: 10.1016/S1364-6613(00)01545-X.
[47] S. Sur and V. K. Sinha, “Event-related potential: An overview,” *Ind. Psychiatry J.*, vol. 18, no. 1, pp. 70–73, 2009, doi: 10.4103/0972-6748.57865.
[48] M. A. Conway, “Episodic memories,” *Neuropsychologia*, vol. 47, no. 11, pp. 2305-2313, 2009, doi: 10.1016/j.neuropsychologia.2009.02.003.
[49] N. Cowan, “Chapter 20 What are the differences between long-term, short-term, and working memory?,” *Progress in Brain Research*, Elsevier, vol. 169, pp. 323–338, 2008, doi: 10.1016/S0079-6123(07)00020-9.
[50] E. Tulving, *Elements of Episodic Memory*, Oxford University Press, 1983.
[51] E. Tulving, “Ebbinghaus’s Memory. What Did He Learn and Remember?,” *J. Exp. Psychol. Learn. Mem. Cogn.*, vol. 11, no. 3, pp. 485-490, 1985, doi: 10.1037/0278-7393.11.3.485.
[52] T. R. Zentall, R. A. Singer, and J. P. Stagner, “Episodic-like memory: Pigeons can report location pecked when unexpectedly asked,” *Behav. Processes*, vol. 79, no. 2, pp. 93-98, 2008, doi: 10.1016/j.beproc.2008.05.003.
[53] L. G. Cheke and N. S. Clayton, “Do different tests of episodic memory produce consistent results in human adults?,” *Learn. Mem.*, bol. 20, no. 9, pp. 491-498, 2013, doi: 10.1101/lm.030502.113.
[54] M. E. Hasselmo, *How we remember: Brain mechanisms of episodic memory*, Cambridge, MA, US: MIT Press, 2012.
[55] B. C. Lega, J. Jacobs, and M. Kahana, “Human hippocampal theta oscillations and the formation of episodic memories,” *Hippocampus*, vol. 22, no. 4, pp. 748-761, 2012, doi: 10.1002/hipo.20937.
[56] D. C. Fitzpatrick, J. M. Roberts, S. Kuwada, D. O. Kim, and B. Filipovic, “Processing temporal modulations in binaural and monaural auditory stimuli by neurons in the inferior colliculus and auditory cortex,” *JARO - J. Assoc. Res. Otolaryngol.*, vol. 10, no. 4, pp. 579-593, 2009, doi: 10.1007/s10162-009-0177-8.
[57] L. Shekar, C. Suryavanshi, and K. Nayak, “Effect of alpha and gamma binaural beats on reaction time and short-term memory,” *Natl. J. Physiol. Pharm. Pharmacol.*, vol 8, no. 6, pp. 829-833, 2018, doi: 10.5455/njppp.2018.8.1246506022018.
[58] J. D. Lane, S. J. Kasian, J. E. Owens, and G. R. Marsh, “Binaural auditory beats affect vigilance performance and mood,” *Physiol. Behav.*, vol. 63, no. 2, pp. 249–252, Jan. 1998, doi: 10.1016/S0031-9384(97)00436-8.
[59] R. Srinivasan and P. L. Nunez, “Electroencephalography,” in *Encyclopedia of Human Behavior: Second Edition*, pp. 15-23, 2012.
[60] R. İnce, S. S. Adanır, and F. Sevmez, “The inventor of electroencephalography (EEG): Hans Berger (1873–1941),” *Child’s Nervous System*, 2020, doi: 10.1007/s00381-020-04564-z.
[61] E. Kamrani, “On-chip integrated functional near infra-red spectroscopy (fNIRS) photoreceiver

for portable brain imaging," PhDT, 2014.
[62] M. H. Libenson, *Practical Approach to Electroencephalography*, 1st ed. Elsevier, 2009.
[63] A. Tandle, N. Jog, P. D'cunha, and M. Chheta, "Classification of Artefacts in EEG Signal Recordings and EOG Artefact Removal using EOG Subtraction," *Commun. Appl. Electron.*, vol. 4, no. 1, pp. 12-19, 2016, doi: 10.5120/cae2016651997.
[64] A. Lau-Zhu, M. P. H. Lau, and G. McLoughlin, "Mobile EEG in research on neurodevelopmental disorders: Opportunities and challenges," *Developmental Cognitive Neuroscience*, vol. 36, p. 100635, 2019, doi: 10.1016/j.dcn.2019.100635.
[65] B. Byrom, M. McCarthy, P. Schueler, and W. Muehlhausen, "Brain Monitoring Devices in Neuroscience Clinical Research: The Potential of Remote Monitoring Using Sensors, Wearables, and Mobile Devices," *Clin. Pharmacol. Ther.*, vol. 104, no. 1, pp. 59–71, 2018, doi: 10.1002/cpt.1077.
[66] P. Bashivan, I. Rish, and S. Heisig, "Mental State Recognition via Wearable EEG," 2016, [Online]. Available: http://arxiv.org/abs/1602.00985.
[67] P. Peining, G. Tan and A. Wai, "Evaluation of Consumer-Grade EEG Headsets for BCI Drone Control," original work, 2017.
[68] S. Pathirana, D. Asirvatham, and G. Johar, "A critical evaluation on low-cost consumer-grade electroencephalographic devices," *2018 2nd International Conference on BioSignal Analysis, Processing and Systems (ICBAPS)*, pp. 160-165, 2018, doi: 10.1109/ICBAPS.2018.8527413.
[69] "Hardware Specifications - Muse Developers." https://web.archive.org/web/20181023155100/http://developer.choosemuse.com/hardware-firmware/hardware-specifications (accessed May 16, 2021).
[70] O. E. Krigolson, C. C. Williams, A. Norton, C. D. Hassall, and F. L. Colino, "Choosing MUSE: Validation of a low-cost, portable EEG system for ERP research," *Front. Neurosci.*, vol. 11, p. 109, 2017, doi: 10.3389/fnins.2017.00109.
[71] A. Barachant, "P300 with Muse EEG headband," 2017. https://alexandre.barachant.org/blog/2017/02/05/P300-with-muse.html (accessed May 17, 2021).
[72] A. Hashemi, L. J. Pino, G. Moffat, K. J. Matherson, C. Aimone, P. J. Bennet, L. A. Schmidt, A. B. Sekuler, "Characterizing population EEG dynamics throughout adulthood," *eNeuro*, vol. 3, no. 6, pp. 1–13, 2016, doi: 10.1523/ENEURO.0275-16.2016.
[73] A. Arsalan, M. Majid, A. R. Butt, and S. M. Anwar, "Classification of Perceived Mental Stress Using A Commercially Available EEG Headband," *IEEE J. Biomed. Heal. Informatics*, vol. 23, no. 6, pp. 2257-2264, 2019, doi: 10.1109/jbhi.2019.2926407.
[74] M. M. Maddox, A. Lopez, S. H. Mandava, A. Boonjindasup, S. Viriyasiripong, J. L. Silberstein, and B. R. Lee, "Electroencephalographic Monitoring of Brain Wave Activity During Laparoscopic Surgical Simulation to Measure Surgeon Concentration and Stress: Can the Student Become the Master?," *J. Endourol.*, vol. 29, no. 12, pp. 1329–1333, 2015, doi: 10.1089/end.2015.0239.
[75] A. Asif, M. Majid, and S. M. Anwar, "Human stress classification using EEG signals in response to music tracks," *Comput. Biol. Med.*, vol. 107, pp. 182–196, 2019, doi: 10.1016/j.compbiomed.2019.02.015.
[76] X. Zhang and Q. Gong, "Frequency-following responses to complex tones at different frequencies reflect different source configurations," *Front. Neurosci.*, vol. 13, p. 130, 2019, doi: 10.3389/fnins.2019.00130.
[77] J. C. R. Licklider, J. C. Webster, and J. M. Hedlun, "On the Frequency Limits of Binaural Beats," *J. Acoust. Soc. Am.*, vol. 22, pp. 468-473, 1950, doi: 10.1121/1.1906629.
[78] M. Garcia-Argibay, M. A. Santed, and J. M. Reales, "Efficacy of binaural auditory beats in cognition, anxiety, and pain perception: a meta-analysis," *Psychol. Res.*, vol. 83, no. 2, pp. 357–372, 2019, doi: 10.1007/s00426-018-1066-8.
[79] L. Stevens, Z. Haga, B. Queen, B. Brady, D. Adams, J. Gilbert, E. Vaughan, C. Leach, P. Nockels, and P. McManus, "Binaural Beat Induced Theta EEG Activity and Hypnotic Susceptibility: Contradictory Results and Technical Considerations," *Am. J. Clin. Hypn.*, vol. 45, no. 4, pp. 295–309, Apr. 2003, doi: 10.1080/00029157.2003.10403543.
[80] H. Pratt, A. Starr, H. J. Michalewski, A. Dimitrijevic, N. Bleich, and N. Mittelman, "A

comparison of auditory evoked potentials to acoustic beats and to binaural beats," *Hear. Res.*, vol. 262, no. 1–2, pp. 34–44, 2010, doi: 10.1016/j.heares.2010.01.013.
[81] "Noise Infographic - Levels by Decibels | NIOSH | CDC." https://www.cdc.gov/niosh/topics/noise/infographic-noiselevels.html (accessed May 25, 2021).
[82] "NIOSH Sound Level Meter App | NIOSH | CDC." https://www.cdc.gov/niosh/topics/noise/app.html (accessed May 25, 2021).
[83] G. Lightfoot, K. Munro, S. Brennan, S. Bell, and C. Georga, "Recommended Procedure Cortical Auditory Evoked Potential (CAEP) Testing," 2016. Accessed: May 28, 2021. [Online]. Available: www.thebsa.org.
[84] "Mindfulness Meditation App for iOS and Android." https://choosemuse.com/muse-app/ (accessed May 29, 2021).
[85] "GitHub - kowalej/BlueMuse: Windows 10 app to stream data from Muse EEG headsets via LSL (Lab Streaming Layer)." https://github.com/kowalej/BlueMuse (accessed May 29, 2021).
[86] C. Kothe, D. Medine, C. Boulay, M. Grivich, and T. Stenner, "Labstreaminglayer 1.13 documentation," 2019. https://labstreaminglayer.readthedocs.io/info/intro.html (accessed May 31, 2021).
[87] "GitHub - labstreaminglayer/liblsl-Matlab: Matlab bindings for liblsl." https://github.com/labstreaminglayer/liblsl-Matlab (accessed May 31, 2021).
[88] "GitHub - labstreaminglayer/App-LabRecorder." https://github.com/labstreaminglayer/App-LabRecorder (accessed May 31, 2021).
[89] "Extensible Data Format (XDF)." https://github.com/sccn/xdf (accessed May 31, 2021).
[90] A. Delorme and S. Makeig, "EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics," *J. Neurosci. Methods*, vol. 134, no. 1, pp. 9–21, 2004.
[91] "EEGLAB Official Tutorial - EEGLAB preprocessing #6: Removing bad channels - YouTube." https://www.youtube.com/watch?v=5BTT-L2Ab04 (accessed Jun. 29, 2021).
[92] J. Lopez-Calderon and S. J. Luck, "ERPLAB: An open-source toolbox for the analysis of event-related potentials," *Front. Hum. Neurosci.*, vol. 8, p. 213, 2014, doi: 10.3389/fnhum.2014.00213.
[93] "Artifact Rejection in Continuous Data · lucklab/erplab Wiki · GitHub." https://github.com/lucklab/erplab/wiki/Artifact-Rejection-in-Continuous-Data (accessed Jul. 28, 2020).
[94] M. B. Brodeur, E. Dionne-Dostie, T. Montreuil, and M. Lepage, "The bank of standardized stimuli (BOSS), a new set of 480 normative photos of objects to be used as visual stimuli in cognitive research," *PLoS One*, vol. 5, no. 5, p. e10773, 2010, doi: 10.1371/journal.pone.0010773.
[95] P. Cape and K. Phillips, "Questionnaire length and fatigue effects: The latest thinking and practical solutions," *Survey Sampling International*, white paper, 2015 [Online]. Available: https://silo.tips/download/white-paper-questionnaire-length-and-fatigue-effects-the-latest-thinking-and-pra
[96] M. Garcia-Argibay, M. A. Santed, and J. M. Reales, "Efficacy of binaural auditory beats in cognition, anxiety, and pain perception: a meta-analysis," *Psychol. Res.*, vol. 83, no. 2, pp. 357-372, 2019, doi: 10.1007/s00426-018-1066-8.
[97] "EEGLAB Automatic Channel Rejection - GitHub." https://github.com/sccn/eeglab/blob/develop/functions/popfunc/pop_rejchan.m (accessed Jun. 03, 2021).
[98] "Design digital filters - MATLAB designfilt." https://www.mathworks.com/help/signal/ref/designfilt.html (accessed Apr. 09, 2021).
[99] A. de Cheveigné and I. Nelken, "Filters: When, Why, and How (Not) to Use Them," *Neuron*, vol. 102, no. 2, pp. 280–293, 2019, doi: 10.1016/j.neuron.2019.02.039.
[100] A. Pluta, C. C. Williams, G. Binsted, K. G. Hecker, and O. E. Krigolson, "Chasing the zone: Reduced beta power predicts baseball batting performance.," *Neurosci. Lett.*, vol. 686, pp. 150–154, 2018, doi: 10.1016/j.neulet.2018.09.004.
[101] "Buffer signal vector into matrix of data frames - MATLAB buffer." https://www.mathworks.com/help/signal/ref/buffer.html (accessed Apr. 09, 2021).
[102] N. Hazarika, J. Z. Chen, A. C. Tsoi, and A. Sergejew, "Classification of EEG signals using the

wavelet transform," *Signal Processing*, vol. 59, no. 1, pp. 61-72, 1997, doi: 10.1016/s0165-1684(97)00038-8.

[103] "1-D wavelet decomposition - MATLAB wavedec." https://www.mathworks.com/help/wavelet/ref/wavedec.html (accessed Apr. 13, 2021).

[104] A. Subasi, "EEG signal classification using wavelet feature extraction and a mixture of expert model," *Expert Syst. Appl.*, vol. 32, no. 4, pp. 1084-1093, 2007, doi: 10.1016/j.eswa.2006.02.005.

[105] H. U. Amin, W. Mumtaz, A. R. Subhani, M. N. M. Saad, and A. S. Malik, "Classification of EEG signals based on pattern recognition approach," *Front. Comput. Neurosci.*, vol. 11, p. 103, 2017, doi: 10.3389/fncom.2017.00103.

[106] L. Guo, D. Rivero, J. A. Seoane, and A. Pazos, "Classification of EEG signals using relative wavelet energy and artificial neural networks," *GEC '09: Proceedings of the first ACM/SIGEVO Summit on Genetic and Evolutionary Computation*, pp. 177-184, 2009, doi: 10.1145/1543834.1543860.

[107] C. P. Doncaster and A. J. H. Davey, *Analysis of Variance and Covariance*. Cambridge: Cambridge University Press, 2007.

[108] "LSL Validation." https://sccn.ucsd.edu/~mgrivich/LSL_Validation.html (accessed Jun. 19, 2021).

[109] M. da Silva Junior, R. C. de Freitas, W. P. dos Santos, W. W. A. da Silva, M. C. A. Rodrigues, and E. F. Q. Conde, "Exploratory study of the effect of binaural beat stimulation on the EEG activity pattern in resting state using artificial neural networks," *Cogn. Syst. Res.*, vol. 54, pp. 1-20, 2019, doi: 10.1016/j.cogsys.2018.11.002.

[110] H. D. Orozco Perez, G. Dumas, and A. Lehmann, "Binaural beats through the auditory pathway: From brainstem to connectivity patterns," *eNeuro*, vol. 7, no. 2, ENEURO.0232-19.2020, 2020, doi: 10.1523/ENEURO.0232-19.2020.

[111] R. Kennerly, "An Empirical Investigation Into the Effect of Beta Frequency Binaural beat Audio Signals on Four Measures of Human Memory," *Hemi-Sync J.*, 1996.

[112] E. Nyhus, "Brain Networks Related to Beta Oscillatory Activity during Episodic Memory Retrieval.," *J. Cogn. Neurosci.*, vol. 30, no. 2, pp. 174–187, 2018, doi: 10.1162/jocn_a_01194.

A. Appendix A

Table A.1 - Results of the two-tailed paired t-tests between AB and BB conditions concerning the first session of the theta group. Significance: *p < 0.05. **p < 0.01. ***p < 0.001.

THETA GROUP, SESSION 1
Level of decomposition

Channel	Segm.	D1 (25-50 Hz)			D2 (13-25 Hz)			D3 (6-13 Hz)			D4 (3-6 Hz)			A4 (0-3 Hz)		
		stat	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*
	1	t = -1.8803	14	0.08103 .	t = -1.897	14	0.07865	t = 2.6729	14	0.0182*	t = 1.5401	14	0.1458	t = 1.9663	14	0.06941
	2	t = -1.1692	14	0.2618	t = -1.1345	14	0.2757	t = 1.791	14	0.09493	t = 0.30261	15	0.7663	t = 2.7272	13	0.01728*
	3	t = -1.3895	14	0.1864	t = -1.4938	14	0.1574	t = 0.22416	14	0.4129	t = 0.08442	15	0.9338	t = 0.99679	15	0.3347
	4	t = -0.50826	15	0.6187	t = -0.53374	15	0.6013	t = 0.087506	14	0.4658	t = -0.31334	15	0.7583	t = 1.1549	15	0.2662
	5	t = -0.53071	15	0.6034	t = -0.52323	15	0.6085	t = 0.6527	14	0.2623	t = -0.15734	15	0.8771	t = 1.2429	15	0.233
	6	t = -1.4677	14	0.1643	t = -1.4508	14	0.1689	t = 0.72478	14	0.2403	t = -0.46721	15	0.6471	t = 1.1541	15	0.2665
TP9	**7**	t = -2.3104	13	0.03792*	t = -2.261	13	0.04155*	t = 0.66616	13	0.2585	t = 0.51964	14	0.6114	t = 2.5913	13	0.02237*
	8	t = 0.22442	14	0.8257	t = 0.197	14	0.8467	t = -1.0952	14	0.854	t = -1.1391	14	0.2738	t = 0.69131	14	0.2503
	9	t = -0.67719	14	0.5093	t = 0.25576	15	0.8016	t = -0.10837	15	0.9151	t = -1.1554	15	0.266	t = 0.24866	15	0.4035
	10	t = 0.10407	14	0.9186	t = 0.014637	14	0.9885	t = -0.65076	13	0.5265	t = -0.6127	14	0.5499	t = 0.75846	14	0.2304
	11	t = -0.19037	14	0.8518	t = -0.23235	14	0.8196	t = -0.79447	14	0.4402	t = -0.48003	14	0.6386	t = 0.64818	14	0.2637
	12	t = 0.70689	14	0.4912	t = 0.68583	14	0.504	t = -1.0066	14	0.3312	t = -0.58518	14	0.5677	t = -0.42673	14	0.662
	13	t = -0.10435	12	0.9186	t = 0.802	14	0.436	t = -1.2379	14	0.8819	t = -0.89255	14	0.8064	t = -0.3077	14	0.6186
	1	t = 0.63319	14	0.5368	t = 0.65146	14	0.5253	t = 0.28466	14	0.7801	t = 0.89698	14	0.3849	t = -1.0667	14	0.3041
	2	t = 0.078208	15	0.9387	t = 0.31722	15	0.7555	t = 0.40775	15	0.6892	t = 1.2276	15	0.2385	t = -0.25303	14	0.8039
	3	t = 0.34434	14	0.7357	t = 0.2498	14	0.8064	t = -0.96276	14	0.352	t = 1.1458	14	0.2711	t = -0.41138	14	0.687
	4	t = 0.29223	14	0.7744	t = 0.34893	14	0.7323	t = 0.21448	13	0.8335	t = -0.158	14	0.8767	t = -0.27979	14	0.7837
	5	t = 0.74641	14	0.4678	t = 0.84939	14	0.41	t = -0.212	14	0.8352	t = -1.2168	14	0.2438	t = -0.59179	14	0.5634
	6	t = 0.049647	14	0.9611	t = 0.1325	14	0.8965	t = 0.20628	14	0.8395	t = -0.080904	14	0.9367	t = 0.90475	13	0.3821
TP10	**7**	t = -0.46335	14	0.6502	t = -0.34126	14	0.738	t = 0.50441	14	0.6218	V = 51	15	0.6387	t = 0.29392	14	0.7731
	8	t = -0.51418	14	0.6151	t = -0.39838	14	0.6964	t = 0.44678	14	0.6619	V = 53	15	0.7197	t = 0.23376	14	0.8186
	9	t = -0.63849	14	0.5335	t = -0.39905	14	0.6959	t = 1.6044	14	0.1309	t = -0.10243	13	0.92	t = -0.161	14	0.8744
	10	t = 0.27372	13	0.7886	t = 0.34804	13	0.7334	t = 0.019152	14	0.985	V = 61	15	0.978	t = 0.16443	14	0.8717
	11	t = -0.3739	14	0.714	t = 0.20474	13	0.8409	t = -0.15052	14	0.8825	V = 61	15	0.978	t = 0.42313	14	0.6786
	12	t = 0.69121	14	0.5007	t = 0.059562	13	0.9534	t = -0.30137	14	0.7676	t = 0.47891	14	0.6394	t = 0.36951	12	0.7182
	13	t = 0.68282	14	0.5059	t = 0.11964	13	0.9066	t = -0.32514	14	0.7499	t = 0.0586	14	0.9541	t = 1.0324	12	0.3222
	1	t = -0.95617	14	0.8224	t = -0.45984	14	0.6527	t = 1.2635	14	0.2271	t = 1.6563	15	0.1184	t = -0.7191	15	0.4831
	2	t = -0.18513	14	0.5721	t = 0.54096	14	0.597	t = 2.3708	14	0.03264*	t = 2.1967	15	0.04417*	t = -1.1432	14	0.2721
	3	t = -0.74385	13	0.4702	V = 46	14	0.4543	t = 0.837	14	0.4167	t = 0.93708	15	0.3636	t = 0.44016	14	0.6665
	4	t = 0.43604	12	0.6705	t = 0.87886	14	0.3943	t = 1.4933	14	0.1575	t = -1.4282	15	0.1737	t = -0.4066	14	0.6904
	5	t = 0.76305	13	0.4591	t = 1.2163	15	0.2427	t = 0.65774	15	0.5207	t = -0.74322	15	0.4688	t = -1.206	15	0.2465
	6	t = -0.12071	14	0.9056	t = 1.1271	15	0.2774	t = 0.79882	15	0.4369	t = -0.024908	15	0.9805	t = -1.2122	15	0.2442
AF7	**7**	V = 84	15	0.04944*	t = 1.6777	15	0.1141	t = 0.75852	15	0.4599	t = -1.1829	15	0.2553	t = -1.3544	15	0.1956
	8	t = -0.30396	14	0.7656	t = 0.75366	14	0.4635	t = 1.2795	15	0.2201	t = -0.52933	15	0.6043	t = -1.4128	15	0.1781
	9	V = 74	14	0.4543	t = 1.6071	15	0.1289	t = 1.5057	15	0.1529	t = -1.0012	15	0.3326	t = -1.4265	15	0.1742
	10	V = 50	13	0.7869	t = -0.18744	13	0.8542	t = -0.18903	14	0.8528	t = -1.5388	13	0.1478	t = -0.28911	14	0.7767
	11	0.21243	12	0.8353	t = -0.98366	14	0.342	t = -1.1856	13	0.257	t = 0.63651	15	0.534	t = -0.3824	15	0.7075
	12	V = 60	13	0.6698	t = -0.31707	14	0.7559	t = 2.1965	14	0.04539*	t = 0.32234	15	0.7516	t = -1.2597	14	0.2284
	13	t = 2.3465	11	0.03873*	t = -0.63538	14	0.7323	t = 1.1695	15	0.2605	t = 0.50658	15	0.6198	t = -0.90415	15	0.3802
	1	t = -1.9579	13	0.07206	t = -0.40504	14	0.6916	t = -0.097316	15	0.9238	t = 3.8405	13	0.002044**	t = -0.56285	15	0.5819
	2	t = -1.4359	13	0.1747	t = 0.17763	14	0.8616	t = 0.43112	15	0.6725	t = 1.436	15	0.1715	t = -0.49974	14	0.625
	3	t = -0.8166	13	0.4289	t = -1.0959	14	0.2916	t = 0.035372	14	0.9723	t = 1.4891	15	0.1572	t = 0.4447	14	0.6633
	4	t = -0.6581	13	0.522	t = 1.0095	14	0.3299	t = 0.74172	15	0.4697	t = 0.025208	15	0.9802	V = 53	14	0.7197
	5	t = -0.20589	14	0.8398	t = 0.55633	14	0.5868	t = 2.3668	14	0.03289*	t = 0.8777	15	0.394	t = -1.3073	14	0.2122
	6	t = -0.038848	14	0.9696	t = 0.97729	14	0.345	t = 0.83473	15	0.2085	t = 0.0051713	15	0.9959	t = -1.5039	15	0.1534
AF8	**7**	V = 76	13	0.1531	t = 1.1559	14	0.2671	t = 0.89175	15	0.1933	t = -1.7743	15	0.09631	t = -1.4709	15	0.162
	8	t = 0.056404	14	0.9558	t = 1.1995	14	0.2502	t = 1.9643	15	0.0683	t = -1.0607	15	0.3056	t = -1.9351	15	0.07206
	9	V = 70	14	0.5995	t = 1.3448	14	0.2001	t = 1.5762	15	0.1358	t = -1.4577	15	0.1655	t = -1.621	15	0.1258
	10	V = 60	14	0.6698	t = 0.11493	13	0.9103	t = -0.47451	14	0.6424	t = -1.6219	15	0.1271	t = -0.2342	14	0.8182
	11	t = 1.6583	12	0.1231	V = 62	14	0.583	t = 0.33947	14	0.7393	t = -0.47612	14	0.6413	t = -0.75807	14	0.461
	12	t = 2.2804	11	0.04351*	t = 0.38453	13	0.7068	t = 2.6583	14	0.01872*	t = -0.09211	14	0.9279	t = -1.3373	13	0.2041
	13	t = 3.0187	11	0.01168*	V = 66	11	0.0009766***	t = 1.9039	14	0.07768	t = -0.78777	14	0.444	t = -0.40731	13	0.6904

Table A.2 - Results of the two-tailed paired t-tests between AB and BB conditions concerning the second session of the theta group. Significance: *p < 0.05. **p < 0.01. ***p < 0.001.

THETA GROUP, SESSION 2

		Level of decomposition														
Channel	**Segm.**	**D1 (25-50 Hz)**			**D2 (13-25 Hz)**			**D3 (6-13 Hz)**			**D4 (3-6 Hz)**			**A4 (0-3 Hz)**		
		stat	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*
	1	t = -2.9275	13	0.01177*	V = 6	14	0.001709**	t = -1.6268	14	0.1261	t = 0.31384	14	0.7583	t = 1.2786	14	0.2218
	2	t = -2.0024	13	0.06655	t = -2.1582	13	0.0502	t = -1.2138	14	0.2449	t = -1.0341	11	0.3233	t = 1.505	14	0.1546
	3	t = -0.31125	13	0.7605	t = -0.28752	13	0.6109	t = 0.15548	13	0.8788	t = 0.34287	13	0.7372	t = 0.13581	13	0.8941
	4	V = 26	14	0.104	t = -1.689	13	0.9425	t = 0.89595	14	0.3854	t = 0.44985	14	0.6597	t = -0.0041308	14	0.9968
	5	V = 26	13	0.3394	t = -0.6681	10	0.7404	t = -0.52042	13	0.6115	t = -0.23402	13	0.8186	t = 0.92393	13	0.3724
	6	V = 41	13	0.7869	V = 43	13	0.583	t = 0.1889	14	0.8529	t = 1.1471	14	0.2706	t = 0.062097	14	0.9514
TP9	**7**	t = 0.13136	13	0.8975	t = -0.12138	13	0.5474	t = -0.29715	14	0.7707	t = 0.89323	14	0.3868	t = 0.81137	14	0.4307
	8	t = -0.51231	12	0.6177	V = 49	13	0.8552	t = -0.73126	14	0.4767	t = 0.17506	14	0.8635	t = 1.3291	14	0.2051
	9	t = -0.58592	12	0.5688	V = 51	13	0.9515	t = -2.0983	12	0.05772 .	t = -0.092033	14	0.928	V = 85	15	0.1688
	10	t = -1.2072	12	0.2506	t = -1.7208	12	0.1109	V = 36	15	0.1876	t = -0.2291	14	0.8221	t = 1.8123	14	0.09143
	11	t = -0.61963	12	0.5471	V = 50	13	0.9032	V = 46	13	0.7148	t = 0.042408	14	0.9668	t = 1.3249	14	0.2064
	12	t = -0.47323	12	0.6445	V = 49	13	0.8552	V = 38	15	0.2293	t = -0.010126	14	0.9921	t = 1.2786	14	0.2218
	13	t = 0.67678	10	0.5139	t = 0.45989	10	0.6554	t = -0.90042	12	0.3856	t = -0.010126	14	0.9921	t = -0.5638	12	0.5833
	1	t = -3.6954	11	0.00353**	t = -4.3814	11	0.001096**	t = -1.0577	12	0.311	t = 0.81549	12	0.4307	t = 3.1629	12	0.008177**
	2	V = 12	12	0.01709*	V = 13	12	0.02148*	t = 1.1314	11	0.2819	t = 1.5189	12	0.1547	t = 1.9344	12	0.07699
	3	V = 21	12	0.09424	t = -1.7093	12	0.1131	t = 1.3592	12	0.1991	t = 2.0077	12	0.06773	t = 0.33247	12	0.7453
	4	V = 23	13	0.06763	t = -1.5508	13	0.145	t = 2.5254	14	0.02425*	t = 1.7997	14	0.09349	t = 0.78028	14	0.4482
	5	V = 16	14	0.01025*	V = 22	14	0.03015*	t = 2.4825	14	0.02634*	t = 2.7722	14	0.01498*	t = 1.4497	14	0.1692
	6	t = -2.1476	14	0.04974*	t = -1.7846	14	0.096	t = 2.0497	14	0.05961	t = 3.4508	14	0.003898**	t = 0.21133	14	0.8357
TP10	**7**	V = 34	14	0.1514	t = -1.6007	14	0.1318	t = 1.5661	14	0.1396	t = 2.4154	14	0.02997*	t = 0.68264	14	0.506
	8	t = -1.4523	14	0.1684	t = -1.0358	14	0.3179	t = 1.3419	14	0.201	t = 0.26476	14	0.7951	t = 0.47692	14	0.6408
	9	t = -0.23099	12	0.8212	t = -0.66362	13	0.5185	t = 0.79762	14	0.4384	t = 0.27599	14	0.7866	t = 1.1311	14	0.277
	10	t = -1.4064	14	0.1814	t = -1.2553	14	0.2299	t = 0.45241	14	0.6579	t = -0.20389	14	0.8414	t = 1.4493	14	0.1693
	11	t = -1.5561	14	0.142	t = -1.2788	14	0.2218	t = 1.7997	14	0.09349	t = 0.45355	14	0.6571	t = 0.7407	14	0.4711
	12	t = -1.7799	14	0.09679	t = -1.5604	14	0.141	V = 75	14	0.4212	t = 0.84171	14	0.4141	t = 0.73118	14	0.4767
	13	t = -1.552	14	0.143	t = -1.3181	14	0.2086	t = 1.8751	14	0.08179	t = 2.5658	14	0.02242*	t = 0.29714	14	0.7707
	1	t = -1.2656	15	0.225	t = -1.2859	15	0.218	t = -0.18078	14	0.8591	V = 51	15	0.4037	V = 82	15	0.4954
	2	V = 35	13	0.2958	t = -0.91507	15	0.3746	t = -0.52262	14	0.6094	t = 0.29237	15	0.774	t = 1.0699	15	0.3016
	3	t = -0.52694	13	0.6071	t = -0.096002	15	0.9248	t = 1.6927	13	0.1143	t = -1.1321	15	0.2754	t = 0.34595	15	0.7342
	4	t = -1.0381	14	0.3168	t = -0.66052	14	0.5196	t = 1.3333	13	0.2053	t = -1.7297	15	0.1042	t = 0.50748	15	0.6192
	5	t = -1.529	14	0.1485	t = -0.52006	15	0.6106	V = 53	15	0.4637	t = -2.7768	15	0.0141*	t = 1.5955	15	0.1315
	6	t = -0.89431	14	0.3863	t = -0.14609	14	0.8859	V = 78	15	0.6322	t = -0.50263	13	0.6236	t = -0.61182	14	0.5505
AF7	**7**	t = -0.6239	14	0.5427	t = -0.19777	14	0.8461	t = 0.79184	14	0.4417	t = -1.4261	15	0.1743	t = -0.19696	15	0.8465
	8	t = -1.212	14	0.2471	t = 0.046765	14	0.9634	t = -0.42876	15	0.6742	t = -1.9668	15	0.06799	t = -0.11112	15	0.913
	9	t = -0.060259	14	0.9528	t = 0.07234	14	0.9434	t = -0.23382	15	0.8183	t = -0.90848	15	0.378	t = -0.28639	15	0.7785
	10	t = -0.47198	14	0.6442	t = -0.062233	14	0.9513	t = -0.45501	15	0.6556	t = -0.92042	15	0.3719	t = -0.13183	15	0.8969
	11	V = 54	13	0.9515	t = 0.22398	14	0.826	t = -0.14198	15	0.889	t = -1.4796	15	0.1597	t = -0.21104	15	0.8357
	12	t = 0.86607	13	0.4022	t = 0.85479	15	0.4061	t = 0.026392	15	0.9793	V = 51	15	0.4037	t = -0.23571	15	0.8168
	13	t = 0.33208	14	0.7448	t = 1.2904	15	0.2164	t = 1.3913	14	0.1858	t = -1.829	15	0.08735	t = -0.69185	15	0.4996
	1	t = -1.9789	13	0.06941	t = -1.7123	15	0.1074	t = -0.73418	14	0.475	t = 0.20807	15	0.838	t = 1.8526	15	0.08372
	2	V = 34	13	0.2676	t = -1.3907	15	0.1846	t = -0.26203	14	0.7971	t = 1.0768	15	0.2986	t = 1.5403	15	0.1443
	3	V = 46	13	0.7148	t = -0.87112	15	0.3974	t = -0.52291	15	0.6087	V = 75	15	0.7436	t = 0.83384	15	0.4175
	4	t = 0.81827	11	0.4306	t = -1.4949	14	0.1571	t = -0.11275	15	0.9117	t = -0.38918	15	0.7026	t = 1.235	14	0.2371
	5	t = 1.7343	11	0.1108	t = -1.3076	14	0.2121	t = -0.82723	15	0.4211	t = -0.82983	15	0.4196	t = 0.95486	15	0.3548
	6	t = 0.68289	12	0.5076	t = 0.65741	13	0.5224	t = -0.12838	15	0.8996	V = 76	15	0.7057	t = -0.61973	15	0.5447
AF8	**7**	t = -0.0616	13	0.9518	t = -0.66203	14	0.5187	t = 0.035476	15	0.9722	t = -0.37892	15	0.7101	V = 72	15	0.8603
	8	t = 0.044192	14	0.9654	t = 0.74091	14	0.471	t = 0.017783	15	0.986	t = -1.1316	15	0.2756	t = -0.9662	15	0.3493
	9	t = 0.57168	14	0.5766	t = 0.62226	14	0.5438	t = -0.421	15	0.6797	t = -1.218	15	0.242	t = -0.58222	15	0.5691
	10	t = 0.12357	14	0.9034	t = 0.24555	14	0.8096	t = -0.39945	15	0.6952	t = -1.7418	15	0.102	t = -0.31614	15	0.7563
	11	t = 1.402	13	0.1843	t = 0.37294	14	0.7148	t = 0.088525	15	0.9306	t = -0.67356	15	0.5108	t = -0.78613	15	0.444
	12	t = 1.5963	13	0.1344	t = 2.5984	13	0.02207*	t = 0.43056	15	0.6729	t = -1.7445	15	0.1015	t = -0.7867	15	0.4437
	13	t = 0.69878	14	0.4961	V = 99	15	0.1167	t = 0.76604	15	0.4555	t = -1.5307	15	0.1467	V = 47	15	0.2979

Table A.3 - Results of the two-tailed paired t-tests between AB and BB conditions concerning the first session of the beta group. Significance: *p < 0.05. **p < 0.01. ***p < 0.001.

BETA GROUP, SESSION 1

Channel	**Segm.**	**D1 (25-50 Hz)**			**D2 (13-25 Hz)**			**D3 (6-13 Hz)**			**D4 (3-6 Hz)**			**A4 (0-3 Hz)**		
		stat	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*
TP9	**1**	t = -2.0383	14	0.06087	t = -2.2895	14	0.0381*	t = -0.22055	14	0.8286	t = -0.11658	14	0.9088	t = 3.4533	14	0.003879**
	2	t = -1.7565	14	0.1008	t = -2.1431	14	0.05016	t = -0.88546	14	0.3909	t = -0.28366	14	0.7808	t = 3.1537	14	0.007039**
	3	t = -1.6312	14	0.1251	t = -1.8638	14	0.08346	t = -0.88044	14	0.3935	t = 0.98022	14	0.3436	t = 2.4493	14	0.02808*
	4	t = -1.6224	10	0.1358	t = -1.7153	14	0.1083	t = -0.58048	14	0.5708	t = 0.53449	14	0.6014	t = 2.3062	14	0.03691*
	5	V = 17	11	0.1682	V = 21	12	0.09424	t = 0.18695	14	0.8544	t = 3.0572	14	0.008527**	V = 64	14	0.8469
	6	t = -1.2378	13	0.2377	t = -1.8316	14	0.08836	t = -0.73931	14	0.4719	t = 1.0411	14	0.3155	t = 1.8055	14	0.09255
	7	t = -0.80388	12	0.4371	t = -2.0121	14	0.06387	t = -0.62984	14	0.5389	t = 0.41095	14	0.6873	t = 2.1717	14	0.04755*
	8	t = -0.4475	12	0.6625	t = -1.1896	13	0.2555	t = 0.11023	14	0.9138	t = 1.0947	14	0.2921	t = 1.2191	14	0.243
	9	V = 25	14	0.04791*	V = 23	14	0.03534*	t = -0.41839	14	0.682	t = -0.64851	14	0.5271	t = 2.6355	14	0.01958*
	10	t = -2.169	14	0.04779*	t = -2.3319	14	0.03516*	t = -0.11824	14	0.9076	t = 0.32809	14	0.7477	t = 2.0708	14	0.05734
	11	t = -1.7179	14	0.1078	t = -1.8641	14	0.08341	t = -1.1	12	0.2929	t = 0.097698	14	0.9236	t = 2.063	14	0.05817
	12	t = -1.5262	14	0.1492	t = -1.5265	14	0.1492	t = 0.048767	14	0.9618	t = 1.9178	14	0.07577	t = 0.74009	14	0.4715
	13	V = 26	14	0.05536	V = 17	14	0.01245*	t = -0.71228	14	0.488	t = 1.6018	14	0.1315	t = 3.0926	14	0.007948**
TP10	**1**	t = -2.0706	13	0.05886	t = -2.325	13	0.0369*	t = -1.0016	13	0.3348	t = -0.30782	13	0.7631	t = 3.3418	13	0.005304**
	2	t = -2.2367	13	0.04346*	t = -2.6827	13	0.0188*	t = -1.3438	13	0.202	t = -0.8626	13	0.404	t = 3.9568	13	0.00164**
	3	t = -1.8917	13	0.08101	t = -2.1151	13	0.05431	t = -1.7922	13	0.09639	t = -0.61855	12	0.5478	t = 2.8365	13	0.01401*
	4	t = -1.9527	13	0.07273	V = 15	13	0.0166*	t = -1.0736	13	0.3025	t = 0.46784	13	0.6476	t = 4.0715	13	0.001322**
	5	t = -1.4674	12	0.168	t = -1.8697	13	0.08421	t = -0.09367	13	0.9268	t = 1.9649	13	0.07116	t = 1.3439	13	0.202
	6	t = -2.1266	13	0.05318	t = -2.1688	13	0.04924*	t = -0.96203	13	0.3536	t = 0.80217	13	0.4369	t = 2.0321	13	0.06309
	7	t = -2.4227	13	0.03075*	t = -2.4177	13	0.03104*	t = -0.13621	13	0.8937	t = 0.027808	13	0.9782	t = 2.2165	13	0.04511*
	8	t = -1.1591	12	0.269	t = -0.9957	12	0.3391	t = 1.0647	13	0.3064	t = 0.77859	13	0.4502	t = 1.0606	13	0.3082
	9	V = 22	13	0.05798	V = 22	13	0.05798	V = 49	13	0.8552	t = -1.1645	13	0.2651	t = 2.2035	13	0.0462*
	10	t = -2.3464	13	0.03547*	t = -2.3286	13	0.03666*	t = -0.67984	12	0.5095	t = 0.17912	13	0.8606	t = 1.8806	13	0.08262
	11	t = -1.873	13	0.08372	t = -1.7317	13	0.107	t = -0.08412	13	0.9342	t = 0.62473	13	0.543	t = 1.3608	13	0.1967
	12	t = -1.513	13	0.1542	t = -1.3407	13	0.203	t = 1.1271	13	0.2801	t = 2.1258	13	0.05326	t = 0.2658	13	0.7946
	13	t = -1.8423	13	0.08835	t = -1.8361	13	0.08931	t = -0.48217	13	0.6377	t = 1.6068	13	0.1321	t = 1.8136	13	0.09288
AF7	**1**	t = -1.2692	11	0.2306	V = 22	12	0.1099	t = -0.40716	13	0.6905	t = 0.75251	14	0.4642	t = 2.649	13	0.02005*
	2	t = -0.71058	11	0.7539	V = 33	12	0.4143	t = 0.46166	13	0.652	t = 1.1972	14	0.2511	V = 85	14	0.1688
	3	t = -0.63982	11	0.5354	t = 0.16996	11	0.8681	t = 0.71424	13	0.4877	t = 1.7561	14	0.1009	V = 75	14	0.4212
	4	t = -1.162	11	0.2698	V = 32	14	0.1205	t = 0.9793	13	0.3453	t = 0.85302	14	0.408	t = 1.5145	14	0.1522
	5	t = -0.43332	11	0.6732	t = -0.79611	12	0.4414	t = 1.1913	13	0.2548	t = 1.5039	14	0.1548	t = 0.95564	14	0.3555
	6	V = 39	12	0.6848	V = 42	14	0.5416	t = 0.61714	13	0.5478	t = 0.12601	14	0.9015	t = 1.16	14	0.2654
	7	V = 34	13	0.2676	V = 31	14	0.107	t = -0.04242	13	0.9668	t = 0.15291	14	0.8807	t = 2.0993	14	0.0544
	8	V = 45	13	0.6698	V = 44	14	0.3894	V = 78	14	0.3303	t = 1.0017	14	0.3335	t = 0.7242	14	0.4809
	9	V = 28	13	0.1353	V = 33	13	0.2412	t = 0.19384	13	0.8493	t = -0.32835	14	0.7475	t = 2.031	14	0.0617
	10	V = 34	13	0.2676	V = 36	14	0.1876	t = 0.28014	13	0.7838	V = 52	14	0.6788	t = 1.3282	14	0.2054
	11	V = 33	13	0.2412	t = -1.7535	14	0.1014	t = 0.32191	13	0.7526	V = 48	14	0.5245	t = 1.5346	14	0.1472
	12	V = 44	13	0.6257	t = -1.1815	14	0.2571	t = 0.64415	13	0.5307	t = 0.55713	14	0.5862	t = 0.31858	14	0.7547
	13	t = -0.37398	12	0.7149	t = -0.80399	13	0.4359	t = 0.004752	13	0.9963	t = 0.71638	14	0.4855	t = 0.73404	14	0.475
AF8	**1**	V = 30	13	0.1726	t = -0.87989	13	0.3949	t = -0.04204	13	0.9671	t = 1.1246	13	0.2811	t = 1.588	14	0.1346
	2	V = 33	14	0.1354	t = -1.4363	14	0.1729	t = -0.09276	13	0.9275	t = 0.53692	14	0.5997	t = 1.5569	14	0.1418
	3	V = 35	13	0.2958	t = -0.98247	13	0.3438	V = 72	14	0.5245	t = 0.95034	14	0.3581	t = 0.75965	13	0.461
	4	V = 30	14	0.0946	t = -1.5784	14	0.1368	t = 0.20769	13	0.8387	t = 1.4219	14	0.177	t = 1.2384	14	0.2359
	5	V = 21	11	0.1763	t = -1.1683	14	0.2622	V = 76	14	0.3894	t = 1.342	14	0.201	t = 0.74922	14	0.4661
	6	V = 28	13	0.1353	t = -1.3181	14	0.2086	t = 0.17116	13	0.8667	t = 0.27739	14	0.7855	t = 1.4666	14	0.1646
	7	t = -1.7649	14	0.09937	t = -1.5222	14	0.1502	t = 0.38484	13	0.7066	t = -0.12799	14	0.9	t = 1.5189	14	0.1511
	8	t = -1.8047	14	0.09267	t = -1.5124	14	0.1527	t = 1.4163	13	0.1802	t = 0.12644	14	0.9012	t = 1.2648	14	0.2266
	9	t = -1.7622	13	0.1015	t = -1.884	14	0.0805	t = 0.73773	13	0.4738	t = -0.49196	14	0.6304	t = 2.1583	14	0.04876*
	10	t = -1.5818	13	0.1377	t = -1.7372	14	0.1043	t = 0.91455	13	0.3771	t = 0.097552	14	0.9237	t = 1.1692	14	0.2619
	11	t = -1.5054	13	0.1561	t = -1.1658	13	0.2646	t = 1.3506	13	0.1999	t = 0.20496	14	0.8406	t = 1.0167	14	0.3266
	12	V = 45	13	0.6698	t = -1.2037	14	0.2487	t = 1.3661	13	0.1951	t = 0.48718	14	0.6337	t = 0.27839	14	0.7848
	13	t = -0.78141	12	0.4497	V = 40	14	0.2769	t = 0.49729	13	0.6273	V = 67	14	0.7197	t = 0.832	14	0.4194

Table A.4 - Results of the two-tailed paired t-tests between AB and BB conditions concerning the second session of the beta group. Significance: *p < 0.05. **p < 0.01. ***p < 0.001.

BETA GROUP, SESSION 1

Channel	Segm.	D1 (25-50 Hz)			D2 (13-25 Hz)			D3 (6-13 Hz)			D4 (3-6 Hz)			A4 (0-3 Hz)		
		stat	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*	*stat*	*df*	*p-value*
TP9	**1**	t = -1.0681	11	0.3084	t = -1.0683	11	0.3083	t = -2.0242	12	0.0658	t = -1.1305	12	0.2804	t = 2.2375	11	0.04691*
	2	t = -0.47733	11	0.6425	t = -0.45892	11	0.6552	t = -0.3532	11	0.7306	t = -0.8307	12	0.4224	t = 1.0464	11	0.3178
	3	V = 46	12	1	V = 43	12	0.8926	t = -0.74326	11	0.4729	t = 0.26081	12	0.7987	t = 0.63537	11	0.5382
	4	t = -0.75405	11	0.4667	t = -0.79039	11	0.446	t = -0.91162	12	0.3799	t = -0.76931	11	0.4579	t = -0.1388	12	0.8919
	5	t = 0.61964	10	0.5494	t = 0.66937	10	0.5184	t = -0.49243	12	0.6313	t = 0.28099	12	0.7835	V = 33	12	0.4143
	6	t = -0.4384	11	0.6696	t = -0.50652	11	0.6225	t = -1.2026	12	0.2523	t = 0.31265	12	0.7599	t = -0.56721	12	0.581
	7	t = -0.0469	11	0.9634	t = -0.044469	11	0.9653	t = -0.035252	12	0.9725	t = 0.74568	12	0.4702	t = -1.1004	11	0.2947
	8	t = -0.38059	11	0.7108	t = -0.40936	11	0.6901	t = -1.0382	12	0.3196	t = -0.28901	12	0.7775	t = 0.53378	11	0.6041
	9	t = -0.50115	11	0.6261	t = -0.57743	11	0.5753	t = -1.1268	12	0.2819	t = 0.10574	12	0.9175	t = 0.5106	11	0.6197
	10	t = -0.44759	11	0.6631	t = -0.50508	11	0.6235	t = -1.2309	12	0.2419	t = 0.73915	12	0.474	t = 0.057904	11	0.9549
	11	t = -0.65345	11	0.5269	t = -0.5798	11	0.5737	t = -1.1165	12	0.2861	t = 0.92283	12	0.3743	t = -0.85333	12	0.4102
	12	t = 0.2739	12	0.7888	t = 0.35961	12	0.7254	t = -0.13454	12	0.8952	t = 1.1071	12	0.29	t = -0.96797	12	0.3522
	13	t = -0.41277	11	0.6877	t = -0.19052	11	0.8524	t = -1.0669	10	0.3111	t = 0.12305	12	0.9041	t = -0.65142	12	0.5271
TP10	**1**	t = 0.26215	11	0.798	t = 0.20609	11	0.8405	t = -1.236	11	0.2422	t = -1.5529	11	0.1487	t = 0.39407	11	0.7011
	2	t = 0.89549	11	0.3897	t = 0.90026	11	0.3873	t = -0.22064	11	0.8294	t = -0.63441	11	0.5388	V = 33	11	0.6772
	3	t = 1.1091	11	0.291	t = 1.0582	11	0.3127	t = -1.5032	9	0.167	t = 0.46147	11	0.6535	t = -1.2599	11	0.2338
	4	t = 0.73744	11	0.4763	t = 0.63787	11	0.5366	t = -1.4537	11	0.174	t = 0.15304	11	0.8811	t = -0.42956	11	0.6758
	5	t = 0.7773	12	0.452	t = 0.71592	12	0.4877	t = -0.69573	12	0.4999	t = 1.0665	12	0.3072	t = -1.1671	12	0.2659
	6	t = 0.54811	12	0.5937	t = 0.50811	12	0.6206	t = -1.2096	12	0.2497	t = 0.73977	12	0.4737	t = -0.69923	12	0.4977
	7	t = 1.4735	12	0.1664	t = 1.5207	12	0.1542	t = 0.04944	12	0.9614	t = 0.98025	12	0.3463	t = -2.4841	12	0.02874*
	8	V = 54	12	0.5879	V = 53	12	0.6355	t = -1.4774	12	0.1653	t = 0.34777	12	0.734	t = -0.58172	12	0.5715
	9	t = 0.88288	12	0.3946	t = 0.77451	12	0.4536	t = -1.7392	12	0.1076	t = 0.8169	12	0.4299	t = -0.82391	12	0.4261
	10	t = 0.7552	12	0.4647	t = 0.67146	12	0.5146	t = -1.7322	12	0.1088	t = 1.0143	12	0.3305	t = -0.90544	12	0.3831
	11	t = 0.20124	11	0.8442	t = 0.17598	11	0.8635	t = -1.5345	12	0.1508	t = 1.207	12	0.2506	t = -1.1093	12	0.289
	12	t = 0.56686	12	0.5813	t = 0.65766	12	0.5232	t = -0.73553	12	0.4761	t = 0.26806	11	0.7936	t = -0.96062	12	0.3557
	13	t = 0.80479	12	0.4366	t = 0.87592	12	0.3983	t = -0.70771	12	0.4926	t = -0.17792	12	0.8618	t = -0.53133	12	0.6049
AF7	**1**	t = -0.77384	11	0.4553	t = -0.95379	12	0.359	t = 1.0082	11	0.335	t = -0.36079	12	0.7245	t = 1.1236	12	0.2831
	2	V = 38	12	0.6355	t = -0.29714	12	0.7714	t = 1.8088	12	0.09559	t = -0.7836	12	0.4484	t = 0.088613	12	0.9309
	3	t = -0.076015	11	0.9408	t = -0.26438	12	0.796	t = 0.4889	12	0.6337	t = 0.18818	12	0.8539	t = -0.038356	12	0.97
	4	t = -0.56713	11	0.582	t = -0.058657	11	0.9543	t = 0.67233	12	0.5141	t = -0.3259	12	0.7501	t = 0.83827	12	0.4183
	5	t = 0.38966	11	0.7042	t = 1.1756	11	0.2646	t = 2.2476	12	0.04419*	t = 0.83387	12	0.2103	t = -1.3483	12	0.8988
	6	t = -0.029632	11	0.9769	t = 0.6132	11	0.5522	t = 1.4598	12	0.17	t = -0.52256	12	0.17	t = -0.15067	12	0.8827
	7	t = 0.88138	11	0.397	t = 0.29411	12	0.7737	t = 2.048	12	0.06309	t = 4.8683	11	0.000496***	t = -1.7323	12	0.1088
	8	t = -0.076579	11	0.9403	t = 0.53728	11	0.6018	V = 61	11	0.09229	t = 2.2262	12	0.04592*	t = -0.16009	11	0.8757
	9	t = -0.98812	11	0.3443	t = -1.0012	12	0.3365	t = 0.94657	12	0.3625	V = 60	12	0.3396	t = -0.17036	12	0.8676
	10	V = 25	12	0.1677	t = -1.2407	12	0.2384	t = 0.5924	12	0.5646	t = 2.2826	12	0.04149*	t = 0.0014994	12	0.9988
	11	t = -1.4822	12	0.1641	t = -0.95832	12	0.3568	t = 0.75023	12	0.4676	t = 1.7858	12	0.09941	t = -0.213	12	0.8349
	12	t = -1.352	12	0.2013	t = -0.88409	12	0.394	V = 49	11	0.4697	t = 1.2901	12	0.2213	t = -0.31408	12	0.7589
	13	t = -1.1508	12	0.2722	t = -0.3161	12	0.7574	t = 1.4424	12	0.1748	t = -0.04105	11	0.968	t = -0.52762	12	0.6074
AF8	**1**	t = -0.28754	11	0.779	t = -0.13574	12	0.8943	t = 0.9506	12	0.3606	t = 0.24316	12	0.812	V = 49	12	0.8394
	2	t = -0.5727	12	0.5774	t = 0.35443	12	0.7292	t = 2.4911	12	0.02838*	t = -0.2494	12	0.5964	t = -1.7635	12	0.1032
	3	t = -1.2578	10	0.237	t = 0.43849	12	0.6688	t = 1.3506	12	0.2017	t = 0.43893	12	0.6685	t = -1.4303	12	0.1781
	4	t = 0.60894	11	0.5549	t = 1.473	11	0.1688	t = 1.403	12	0.186	t = -0.36858	12	0.7189	t = -1.1886	12	0.2576
	5	V = 44	12	0.946	t = 0.90173	12	0.3849	t = 2.3382	12	0.03751*	t = 1.0121	12	0.3314	t = -2.0014	12	0.06848
	6	t = -0.2789	11	0.7855	t = 0.0077754	12	0.9939	t = 1.763	12	0.1033	t = -0.13521	11	0.8949	t = -0.88274	12	0.3947
	7	t = 0.23266	11	0.8203	t = 0.50891	12	0.62	t = 2.0509	12	0.06278	V = 44	8	0.007812**	t = -1.249	11	0.2376
	8	t = -0.089066	11	0.9306	t = -0.6324	11	0.54	V = 71	12	0.08032	t = 2.9844	12	0.01139*	t = -0.8221	11	0.4285
	9	t = -0.99117	11	0.3429	t = -0.62618	12	0.5429	t = 0.97759	12	0.3476	t = 2.0948	12	0.05808	t = -0.21469	12	0.8336
	10	t = -1.4316	12	0.1778	t = -0.34617	12	0.7352	t = 0.14678	11	0.886	t = 2.3856	12	0.03441*	t = 0.67048	11	0.5164
	11	t = -1.3781	12	0.1933	t = -0.48068	12	0.6394	t = 1.1131	12	0.2875	t = 1.5418	12	0.1491	t = -0.334	12	0.7441
	12	t = -1.0849	12	0.2993	t = -0.13317	12	0.8963	V = 71	12	0.08032	t = 1.2935	12	0.2202	t = 0.045342	11	0.9646
	13	t = -1.0145	12	0.3303	t = 0.13706	12	0.8933	t = 1.6101	11	0.1357	t = 0.70121	12	0.4965	t = -0.079784	11	0.9378

Level of decomposition: D1–A4