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Evaluation of Meditation Practice Using a Physiological Computing Mobile Application

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Abstract

Meditation research has been a topic of increasing interest over the past decades. However, scientific research in this area is experiencing several drawbacks, such as the troublesome definition of meditation, adequate study designs and variable outcomes. In the present study, the physiological changes occurring during meditation practice were evaluated by means of a headband capable of acquiring electroencephalography (Fp1 and Fp2 locations) and photoplethysmography signals simultaneously, using a mobile application. A total of 19 participants were divided in two groups: meditators (10 participants, aged between 34–58 years, with a total experience of 1587.9 $\pm$ 2814.8 h) and non-meditators (9 participants, aged between 21–61 years). The meditation practices considered in this study were divided into three main categories: focused attention (4 participants), open monitoring (4 participants) and compassion (2 participants). The differences between meditators and non-meditators (control group), meditation practices and the effects of a daily practice as opposed to a regular meditation practice were evaluated. In order to do so, three periods of acquisition were considered, such as baseline, meditation and post-meditation. The main differences between groups for the electroencephalography analysis were found during each period for the relative alpha power band, for the right and left hemispheres and combination of both hemispheres of the prefrontal brain. Additionally, the meditation period in comparison to baseline mainly revealed decreases in the absolute theta, alpha and beta power, as well as a decrease in relative beta power. The control group showed decreases in the same measures but mainly on the right hemisphere. The relative delta power and theta/beta ratio showed an increase between baseline and meditation periods, which may indicate a shift in brain function for greater detachment combined with greater levels of attention for the meditator group. There were no significant differences between the meditation practices nor in the frequency of practice for the electroencephalography analysis. The photoplethysmography analysis revealed lower RR-intervals during each period as well as lower breathing rate during baseline period for the meditator group. The average and maximum heart rate were significantly higher for meditator group. Additionally, the control group showed lower standard deviation of the heart rate and low frequency power during baseline and post-meditation periods in comparison to the meditators. The meditation period mainly revealed increases in the frequency domain measures, for both groups. The focused attention meditation practices revealed greater sympathetic activation in comparison to the open monitoring practices. In summary, meditation practice revealed significant differences between the meditator and control groups, both in brain activity and in cardiac activity, which may imply that its practice over time results in altered traits. Additionally, this study showed that meditation practice alters the physiological signals of electroencephalography and photoplethysmography according to task, i.e. relaxation or meditation, which allows to identify its state effects.

Keywords: meditation, electroencephalography, photoplethysmography, focused attention, open monitoring

Resumo

A investigação na meditação tem sofrido um crescente interesse nestas últimas décadas. No entanto, a investigação nesta área tem vindo a ser alvo de inúmeras críticas, uma vez que muitos estudos apresentam problemas a nível da definição do estado ou prática de meditação, metodologia escolhida e consequentes resultados variados. Existem inúmeras técnicas de meditação, pelo que fica ao critério do investigador descrevê-la o mais sucintamente possível e clarificar se o estudo se refere à sua prática ou estado alterado que resulta da sua prática. Adicionalmente, fica também ao encargo do investigador decidir se pretende avaliar uma prática de meditação num dado momento, em grupos diferentes – estudo transversal –, ou ao longo de um certo período de tempo, em indivíduos do mesmo grupo – estudo longitudinal. Deve também ser escolhida a melhor métrica para avaliar a experiência total em meditação de um dado indivíduo, como por exemplo uma estimativa do número de horas de prática formal. Devido a esta variabilidade das práticas de meditação e escolha de metodologia, surgem inúmeros resultados e muitos até contraditórios. Devido a estes obstáculos, ainda não existe um consenso entre investigadores na área da meditação. Este tema apresenta detalhes muito minuciosos, pelo que o sucesso na sua investigação poderá passar pela comunicação entre a ciência e as práticas contemplativas, incluindo também uma aprendizagem da parte dos investigadores acerca destas mesmas práticas e tradições.

O presente estudo teve como objetivo principal estudar as alterações fisiológicas resultantes da prática de meditação. Para tal foi utilizada uma banda elástica capaz de adquirir simultaneamente sinais de eletroencefalografia e fotopletismografia, através de sensores colocados na região pré-frontal dos hemisférios esquerdo e direito e no lóbulo da orelha, respetivamente, e uma aplicação de telemóvel que recebia estes sinais. No total 19 participantes foram divididos em dois grupos: praticantes de meditação (10 participantes, com idades entre 34 – 58 anos, com experiência total de meditação de 1587,9 $\pm$ 2814,8 h) e não praticantes de meditação (9 participantes, com idades entre 21–61 anos). As práticas de meditação consideradas neste estudo foram subdivididas em três categorias principais: atenção focada (4 participantes), monitorização aberta (4 participantes) e compaixão (2 participantes). Foram avaliadas as diferenças entre praticantes de meditação e não praticantes (grupo de controlo), práticas de meditação e os efeitos de uma prática diária comparativamente uma prática de meditação regular, i.e. entre 3–4 dias por semana. Para tal, foram considerados três períodos de aquisição: pré-meditação, meditação e pós-meditação, com duração de 2, 10 e 2 minutos, respetivamente.

Uma vez que os sinais de eletroencefalografia podem conter inúmeros artefactos, como a saturação do amplificador operacional (ampop) e artefactos oculares, foi necessário proceder a um pré-processamento do sinal para os eliminar. A saturação do ampop é facilmente identificada, uma vez que aparece no gráfico como uma linha reta. De forma a identifcar e eliminar estas zonas de saturação, o sinal foi divido em segmentos de 1 s, e cada segmento que continha mais de 10 pontos seguidos superiores a 490

unidades arbitrárias era identificado e posteriormente eliminado. Para corrigir os artefactos oculares, o sinal de eletroencefalografia foi primeiramente filtrado usando um filtro Butterworth passa-banda entre 1 e 40 Hz. De seguida, os artefactos oculares foram corrigidos usando a Transformada de Ondeleta Discreta de nível de decomposição 6 e ondeleta Coiflet 3 (coif3). Uma vez que estes artefactos estão presentes em frequências mais baixas, apenas os coeficientes de detalhe entre os 3º e 8º níveis foram submetidos a um limiar estatístico, nos quais valores superiores a esse valor eram igualados a zero. Para obter o sinal de eletroencefalografia corrigido somou-se todos os coeficientes de detalhe e aproximação. Este passo intermédio permitiu corrigir o sinal de eletroencefalografia, sem resultar numa perda de informação. Após o pré-processamento dos sinais de eletroencefalografia, foi utilizada a Transformada de Ondeleta Contínua, usando a ondeleta Morlet para extrair as seguintes métricas: potência absoluta e relativa (das ondas delta, teta, alfa, beta e gama), rácios beta/(alfa + teta), teta/beta e alfa/beta, assimetria das ondas alfa, excitação e valência. As principais diferenças entre os grupos na análise dos sinais de eletroencefalografia foram na menor potência relativa das ondas alfa durante todos os períodos, tanto no hemisfério pré-frontal direito, esquerdo e soma de ambos os hemisférios, para o grupo de praticantes de meditação comparativamente ao controlo. Além disso, entre os períodos de pré-meditação e meditação o grupo de praticantes de meditação apresentou maioritariamente diminuições nas potências absolutas das ondas teta, alfa e beta no hemisfério esquerdo, assim como uma diminuição na potência relativa das ondas beta no hemisfério direito. O grupo de controlo revelou diminuições nestas mesmas ondas mas principalmente do hemisfério direito. A potência relativa das ondas delta e o rácio teta/beta também aumentou durante o período de meditação comparativamente ao período de pré-meditação, o que pode indicar uma mudança na função cerebral para um maior desapego juntamente com níveis de atenção mais elevados para o grupo de praticantes de meditação. Para o grupo de praticantes de meditação, as diferentes práticas de meditação assim como a frequência da prática não apresentaram diferenças significativas entre elas para a análise de eletroencefalografia.

O pré-processamento dos sinais de fotopletismografia consistiu numa filtragem dos mesmos através de um filtro passa-baixo de frequência de corte de 3 Hz. Posteriormente, a análise do sinal filtrado foi feita no domínio do tempo e da frequência. Através da deteção dos picos R foi possível calcular as seguintes métricas (quer no domínio temporal e da frequência): média dos intervalos-RR, desvio padrão dos intervalos-NN, média, desvio padrão, valor mínimo, e valor máximo da frequência cardíaca, raiz quadrada média de diferenças sucessivas, percentagem de intervalos-NN superiores a 50 ms, potências das frequências muito baixa, baixa, alta e total, rácio das frequências baixa/alta, frequências baixa e alta normalizadas, picos das frequências muito baixa, baixa, alta e média da frequência respiratória. A análise dos sinais de fotopletismografia apresentou diferenças significativas entre grupos, entre as quais a média dos intervalos-RR mais baixos em todos os períodos, assim como uma frequência respiratória mais baixa durante o período de pré-meditação para o grupo de praticantes de meditação (comparativamente ao controlo). Adicionalmente, a frequência cardíaca média e máxima foram significativamente mais elevadas para o grupo de praticantes de meditação. Além disso, este mesmo grupo apresentou um desvio padrão da frequência cardíaca e potência da frequência baixa maiores durante os períodos de pré-meditação e pós-meditação em comparação com o grupo de controlo. A comparação entre o período de pré-meditação e de meditação apresentou principalmente aumentos nas medidas do domínio da frequência, para ambos os grupos. As práticas de meditação de atenção focada apresentaram uma maior ativação simpática em comparação com as práticas de monitorização aberta.

Em resumo, a prática de meditação revelou de facto diferenças significativas entre os grupos de

praticantes de meditação e controlo, quer na atividade cerebral quer na atividade cardíaca, o que implica que a sua prática ao longo do tempo resulta em traços alterados. Estes traços alterados verificados podem ser indicadores de um estado alterado de consciência, ou como é tradicionalmente referido no contexto das práticas contemplativas como *samadhi*, *nirvana*, ou iluminação. No entanto, ainda não é conhecido com certeza absoluta quais as características do mesmo. É também de referir que o principal propósito destas práticas contemplativas não é apenas alterar momentaneamente o estado do seu praticante durante a sua prática, mas que estas alterações vão para além da sua prática formal e se tornem parte de um novo estado "natural" do praticante. Este estudo mostrou que a prática de meditação altera os sinais de eletroencefalografia e fotopletismografia de acordo com a tarefa, i.e. relaxamento ou meditação, o que permite identificar os seus efeitos de estado. No entanto, estes efeitos de estado podem também ser diferentes de acordo com o tipo de prática e nível de experiência do praticante. Contudo, o objetivo principal será sempre o mesmo, i.e. alcançar um estado ou traço alterado (estado alterado de consciência). Para concluir, este estudo apresentou algumas limitações, das quais se salienta o número reduzido da amostra, incluir diferentes práticas de meditação e o local de aquisição dos sinais fisiológicos não ser um ambiente controlado. No entanto, estas últimas duas limitações tinham como objetivo possibilitar tanto uma prática como um local mais confortável e familiar aos sujeitos.

Palavras-Chave: meditação, eletroencefalografia, fotopletismografia, atenção focada, monitorização aberta

Contents

List of Acronyms

ADHD	Attention Deficit Hyperactivity Disorder
ANS	Autonomic Nervous System
BR	Breathing Rate
cA	Approximate Coefficients
cD	Detail Coefficients
CMP	Compassion
CWT	Continuous Wavelet Transform
DWT	Discrete Wavelet Transform
ECG	Electrocardiography
EEG	Electroencephalography
EMG	Electromyography
EOG	Electrooculography
FA	Focused Attention
FFT	Fast Fourier Transform
HF	High Frequency
HPF	High-Pass Filter
HR	Heart Rate
HRV	Heart Rate Variability
LED	Light-Emitting Diode
LF	Low Frequency
LPF	Low-Pass Filter
OA	Ocular Artefacts
OM	Open Monitoring
pNN50	Percentage of successive NN-intervals that differ by more than 50 ms
PNS	Parasympathetic Nervous System
PPG	Photoplethysmography
PSD	Power Spectral Density
RIAV	Respiratory-Induced Amplitude Variation

RIFV	Respiratory-Induced Frequency Variation
RIIV	Respiratory-Induced Intensity Variation
RMSSD	Root Mean Square of Successive Differences
RSA	Respiratory Sinus Arrhythmia
SDANN	Standard Deviation of the Average NN-interval
SDNN	Standard Deviation of NN-intervals
SNS	Sympathetic Nervous System
ST	Statistical Threshold
VLF	Very Low Frequency
WT	Wavelet Transform

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Chapter 1

Introduction

The human brain is a powerful and fascinating machine not yet entirely understood by ourselves. Contemplative practices, also referred to as meditation practices, have been studying the mind for thousands of years and it is believed that through their exercise one can attain true and lasting happiness (Rinpoche, 2004). This true happiness, or liberation of suffering, is achieved when one studies their own mind through the exercise of meditation, and in doing so unlocking the mind's true potential. Theoretically, these meditation practices aim at achieving a meditative state, which ultimately result in an altered state of consciousness – also referred to as enlightenment, *nirvana*, *samadhi*, *satori*, *kensho*. The first written evidence of these contemplative practices was found in ancient religious texts, the Vedas. Nonetheless, contrary to popular belief, meditation practices are found across many different religions and beliefs, and not only in Hinduism and Buddhism traditions. Both Christianism and Islamism have their own form of meditation practices, such as prayer. Meditation practices go even beyond religion, and are also found in martial arts, which use breathing techniques and even include some philosophical concepts found in ancient texts.

These altered states of consciousness originating from contemplative practices began to intrigue scientists, and for the last six decades researchers from all around the world have been conducting studies in this area. Since then, researchers in this area have been trying to understand how meditation influences the physiological signals of the human body, what are its short- and long-term effects, if it is always beneficial, and if not, elucidate its controversial side effects. Somewhat recently meditation research has experienced a significant growth in its interest and eventually published articles. During the last five years, over 500 and 1500 articles containing the keywords *meditation* (Figure 1.1a) and *mindfulness* (Figure 1.1b) were published each year, respectively.

1. INTRODUCTION

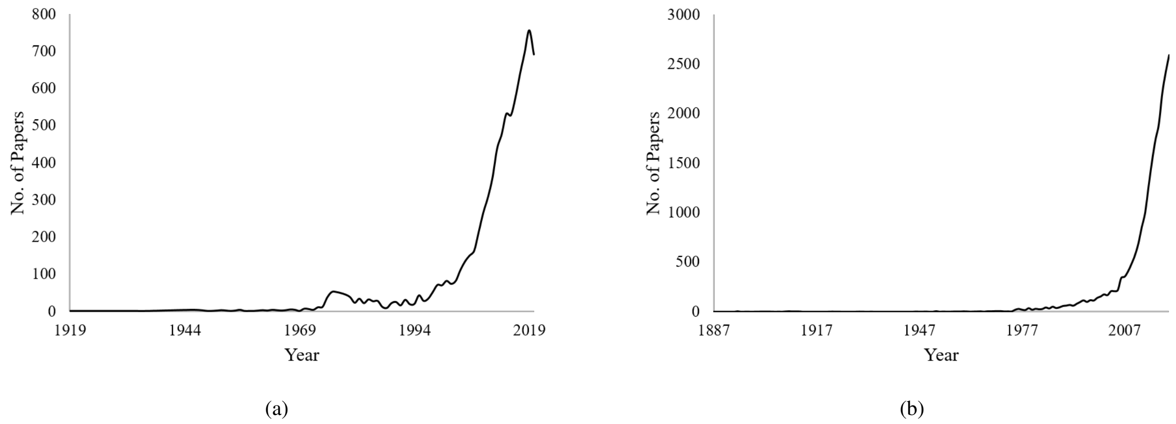


Figure 1.1: Number of papers published each year containing the keywords (a) *meditation* (extracted from https://pubmed.ncbi.nlm.nih.gov/?term=meditation) and (b) *mindfulness* (extracted from https://pubmed.ncbi.nlm.nih.gov/?term=mindfulness).

This sudden interest in meditation research was partially caused by the exaggerated claims and benefits of its practice cultivated by the media, specifically regarding mindfulness (Van Dam et al., 2018). This has led to a public confusion and indifferent use of the terms meditation and mindfulness. According to nowadays articles, each of these terms may be referring to a broad list of ambiguous mental states or practices, and either be associated with a variety of religious contexts, or not related to religion at all, such as Mindfulness Based Stress Reduction Program (Kabat-Zinn, 1990). Ultimately, this culminated in what is one of the most challenging obstacles in meditation research – what is the definition of meditation. Although it seems a simple question, it has not yet been possible to achieve a universal consensus amongst scientists. The definition of meditation in the scientific context appears to be a troublesome topic. Some researchers refer to meditation as a mental state, while others refer to it as a practice, or group of practices. Whether one defines meditation as a state of consciousness or as a practice, or groups of practices, it should be in the researchers interest to succinctly explain its context, and if applicable its religious background (Goleman and Davidson, 2018). Numerous modern studies conducted in this area are a result of a misinterpretation of the contexts of meditation, and why so many of them failed to understand its implications. In addition to this challenging definition, meditation research also exhibit methodological issues. These include poorly designed methodology, inadequate control groups and conditions and reduced sample size.

Modern meditation research seems to be in the middle of a crossroad, due to its challenging definition and methodological issues. Nevertheless, it is advancing towards a better path, and there are many promising results. The Mind & Life Institute[1], founded by Tenzin Gyatso, Francisco Varela and Adam Engle, was created in order to clarify both scientific and contemplative knowledge and ensure the objective analysis of these contemplative practices. For this reason, the main motivation behind this study is to achieve an objective analysis regarding meditation practices and understand the changes in the physiological processes arising from these practices.

This present study is composed of five chapters, the content of which is described below. The present Chapter 1 provides a brief introduction to meditation research, as well as a background of the techniques used to measure physiological signals evaluated in this study. These techniques include the Photoplethysmography (PPG) and Electroencephalography (EEG), which monitor the cardiovascular system and elec-

[1] https://www.mindandlife.org/about/

trical activity of the brain, respectively. A detailed description of each of these signals is provided, as well of some of their clinical applications. A comprehensive review of the meditation investigation is also presented in this section. This review contains the main findings of meditation, as well as the controversy outcomes presented by some researchers. Chapter 2 describes the methodology used in this study, such as the selection and characterization of the participants, as well as the meditation technique practiced by them. This chapter also provides a description of the algorithms used for the pre- and post-processing of the PPG and EEG signals. These include artefact detection and correction for the EEG signals, and peak detection for PPG signals. Chapter 3 provides the statistically significant results of this study. Chapter 4 provides the discussion of the results and a critical analysis of them in comparison to other studies. Additionally, some limitations of the current study are presented. Chapter 5 concludes the study and provides a summary of the outcomes of this study.

1.1 Electroencephalography

EEG is a non-invasive technique that provides information about the electrical activity of the brain. This electrical activity is a summation of the inhibitory and excitatory postsynaptic potentials, mainly in pyramidal cells, which occur in the upper layers of the cortex (Keenan et al., 2013, p.66–70). The cerebral cortex is the outermost layer of the brain and is largely responsible for cognitive processes such as perception, memory, thinking and emotions. These processes involve electrical activity occurring over a 10 ms range. EEG is one of the very few techniques that provides enough temporal resolution to accompany these changes (Srinivasan and Nunez, 2012). It is recorded by placing surface electrodes over the scalp and is a very useful and safe technique for neurology and neurophysiology. One of its main application is for diagnosis of epilepsy and seizure monitoring. EEG also allows the indirect mapping of structural abnormalities, such as brain tumours and stroke location. However, it can be somewhat inaccurate and provide unreliable indication of the type of pathology, and for this reason, neuroimaging techniques provide much trustworthy results. Nonetheless, EEG provides information about the function of the brain and it is still effective as a complementary exam.

The EEG is used to evaluate the changes in mental states, or altered levels of consciousness, and this is one of the reasons why it is a very popular technique amongst meditation studies, besides being cheaper than many imaging methods. The continuous EEG monitoring provides information about the functional changes of the brain and therefore improve its clinical relevance. It provides a great temporal resolution however it lacks spatial resolution in comparison to other functional imaging methods, such as Positron Emission Tomography and Magnetic Resonance Imaging. On the other hand, these imaging methods have a poor temporal resolution, in the order of seconds.

The sampling rate is an important factor to consider when planning for an EEG exam. The sampling rate is the number of points acquired, i.e. recorded, per second. However, according to the Nyquist-Shannon theorem, in order to correctly reproduce a signal, the sampling rate must be at least twice the highest frequency expected to occur in the signal. Otherwise, it will result in aliasing, i.e. artefacts or distortion. Frequencies that exceed half of the sampling frequency will be encoded as lower frequencies. Additionally, EEG recordings may contain a variety of artefacts, due to electrode placement, recording equipment and environment. These artefacts are usually due to movement, ocular movements, muscle, respiratory and cardiac activity, or other reasons, such as electrode popping, electric and alternating current, etc.

1.1.1 Brain Waves

Brain waves, or neural oscillations, represent different patterns of neuronal activity and are described in terms of its frequency components, ranging from 1 to 100 Hz. These frequency components are divided into five different bands shown on Table 1.1. An awake state is characterized by alpha, beta and gamma waves, i.e. faster and lower amplitude brain patterns. Theta and delta waves are rare in a vigilant state.

Table 1.1: Basic human brain waves and frequency ranges (adapted from Abhang et al., 2016a).

Brain Wave	Frequency (Hz)
Delta	1 – 4
Theta	4 – 8
Alpha	8 – 12
Beta	12 – 35
Gamma	> 35

1.1.1.1 Delta Waves

Delta waves are the highest in amplitude but lowest in frequency, i.e. the slowest wave. They are more common in infants and young children, and are associated with deep relaxation. Delta waves are very prominent in brain injuries, learning disabilities, severe Attention Deficit Hyperactivity Disorder (ADHD), and trouble to think (Abhang et al., 2016b). When found in adults, it is associated with deep stages of sleep.

1.1.1.2 Theta Waves

Theta waves are typically found in frontal and central regions of the cortex, and are related to focus, concentration, drowsiness and elevated emotional states (Scher, 2017). Frontal theta band amplitude tend to increase as tasks require more focused attention. Theta waves may appear during a relaxed wakeful state. The highest frequencies of theta rhythms, i.e. slow alpha variant, attenuate with eye opening. They are more commonly found in children and become less prominent as they grow, however it can be found in young adults in temporal regions of the brain and during hyperventilation.

1.1.1.3 Alpha Waves

Alpha waves are typically found in posterior regions of the head during wakefulness, and in central or temporal regions as well. The alpha waves are well seen when the subject is in a relaxed and eye-closed state, also called the classic alpha rhythm. Immediately after eye-closing, it is observed the squeak phenomenon, where alpha frequency increases rapidly, but not permanently (Aminoff, 2012). This rhythm is attenuated by eye-opening and visual tasks, and it is affected by sensory stimuli or other mental activities, such as mathematical problems or anxiety. The alpha waves can be 50 % greater in amplitude in the right hemisphere, typically the non-dominant one. Differences of more than 1 – 2 Hz between the two hemispheres are considered abnormal. Typically, the side with the slower rhythm, i.e. lower frequencies, is most likely to be the abnormal one. Given that the frequency of alpha waves decrease with age, this rhythm can be considered a correlate of cognitive function regulation.

1.1.1.4 Beta Waves

Beta waves may be found in different regions of the cortex, but occur more frequently in frontal or central areas when compared to posterior regions (Kropotov, 2010). Its response to eye-opening can be found in posterior regions of the brain and can be viewed as the fast variant of the alpha waves. It has an amplitude of less than 30 μV. Frequencies between 18 – 25 Hz are often present during drowsiness, light sleep and rapid eye movement sleep, but can also be enhanced during cognitive tasks. It is associated with focused attention, and according to Hans Berger, who first described this rhythm, are the concomitant of mental activity. Beta waves are common in an awake state, and are involved in conscious thought and logical thinking. The prominence of this wave is related to anxiety, inability to relax, stress. On the contrary, its suppression has been associated with ADHD, poor cognition and depression. The balance of these waves help focus, memory and problem solving.

1.1.1.5 Gamma Waves

Gamma waves are very difficult to record and are associated with the active processing of information of the cortex (Abhang et al., 2016b). They have also been associated with conscious visual perception and problem solving. Gamma waves only occur in an awake state and are mainly observed during alertness and after sensory stimulation, possibly linking various information and coordinate sensory and motor activity.

1.2 Photoplethysmography

PPG is a non-invasive optical measurement technique which detects the volumetric changes of blood in microvascular tissue (Sun and Thakor, 2016). It is composed by a light source, typically a light-emitting diode (LED), and a photodetector. The light emitted by the LED illuminates the tissue and is absorbed by surrounding constituents, such as arterial and venous blood, bone and skin. The absorption of the light can be constant, for instance in bone, skin and venous blood, or irregular, such as for arterial blood. The photodetector convert the light energy into electric current, and measures the small changes in light intensity according to changes in blood volume throughout time. Typically, the PPG operates at longer wavelengths, such as red or a near infrared, however shorter wavelengths can also be used to detect superficial blood flow, for instance green and blue.

The PPG can operate in two different modes, depending on the location of the photodetector relative to the light source: transmittance mode and reflective mode. In the transmittance mode, the photodetector is placed on the opposite side of the light source and measures the transmitted light through the tissue. In the reflective mode, or adjacent mode, the photodetector it placed next to the light source and measures the backscattered light from the tissue.

PPG has a number of clinical applications, such as physiological monitoring (such as breathing rate (BR), heart rate (HR), blood oxygen saturation and blood pressure), vascular assessment (such as arterial compliance, arterial disease and endothelial assessment), and autonomic function (such as heart rate variability (HRV) and thermoregulation). The most distinctive waveform of the PPG is the peripheral pulse, which is synchronized to each heartbeat. The pulsatile component, which is also called the AC component of the PPG waveform, is characterized by two phases: anacrotic phase and catacrotic phase (Hertzman, 1937). The first one is the increasing line of the PPG pulse and reflects the systole. The catacrotic phase concerns the decreasing line of the pulse and reflects the diastole. During this phase it is usually observed a dicrotic notch in healthy subjects. Besides the AC component, there is also a slow varying baseline called DC component, due to the constant absorption and scattering of light. The slow varying DC component of the PPG can be due to respiration, vasomotor and vasoconstrictor activity, and thermoregulation. The respiratory induced variations in the PPG are show in Table 1.2.

Table 1.2: Respiratory induced variations in the PPG signal (adapted from Dehkordi et al., 2018).

Name	Description
RIIV	Respiratory-Induced Intensity Variation represents the variations in venous return as a result of the changes in intra-thoracic pressure, which decrease during inspiration and result in an increase in venous return, and vice-versa.
RIAV	Respiratory-Induced Amplitude Variation represents the volume changes during respiration. The left ventricular stroke volume decreases during inspiration due to changes in intra-thoracic pressure, resulting in decrease pulse amplitude, and vice-versa.
RIFV	Respiratory-Induced Frequency Variation represent the variation in HR throughout the respiratory cycle, which increase during inspiration, and vice-versa. This phenomenon is called respiratory sinus arrhythmia (RSA) and is a result of the autonomic regulation of HR during respiration.

These respiratory induced variations are different for both sexes. As a result, the shape of the PPG is different for each subject, and varies depending on the sex and location of the sensor. The common locations of the PPG include the earlobe, forehead, finger, foot and wrist (Allen, 2007). The respiration and peripheral circulation are related, and the RIIV provides information about the venous return to the heart. The RIAV and RIIV components of the PPG signal are sensitive to dehydration and hypovolemia, whereas the RIFV component may be affected in the presence of diseases and disorders (Dehkordi et al., 2018).

1.2.1 Breathing Rate

The normal respiratory rate, or BR, for an adult is 12 – 20 breaths per minute (breaths/min). BR values below 12 and over 20 breaths/min are classified as bradypnea and tachypnea, respectively. The respiratory rate is the only vital sign under voluntary and conscious control, and may change if one brings their attention to it. For this reason, it should be measured without the subject's knowledge. It may influence other physiological measures, such as the HR and HRV. Abnormal respiratory rate is a predictor for diseases, such as pneumonia and cardiac arrest, and in some cases the relative change in BR are more significant than changes in HR and systolic blood pressure (Subbe et al., 2003). Researchers have mentioned that there is no accurate and reliable measurement of BR, whether is performed manually or using a monitoring device (Lovett et al., 2005). However, the PPG signal contains breathing envelopes which can be used to estimate the number of breaths per minute, as shown in Figure 1.2.

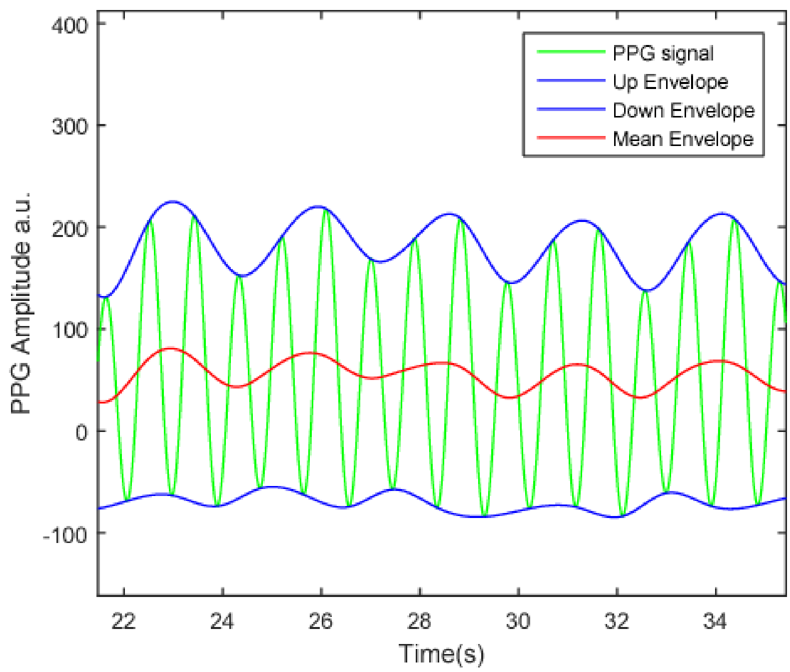


Figure 1.2: The breathing envelope extracted from PPG signals (extracted from Fusco et al., 2015).

1.2.2 Heart Rate

The HR is an important physiological measure which expresses the number of contractions of the heart per minute, i.e. beats per minute (bpm). It is an indirect and objective measure of the status of the cardiovascular system. This measure is strongly influenced by the Autonomic Nervous System (ANS), which is divided into two constituents: the Sympathetic Nervous System (SNS) and the Parasympathetic Nervous System (PNS). The SNS and PNS typically have opposing effects, and generally the PNS is responsible for ensuring homeostasis, whereas SNS is responsible for preparing the organism to react to stressful events (fight-or-flight response). In reality, the HR generally has a small impact on cardiac output, which is mainly controlled by venous pressure (Downey and Heusch, 2001, p.61–69). The normal HR is around 60 – 100 bpm, and lower HR values are typically associated with more efficient heart function. In general, resting HR values of less than 60 bpm are classified as bradycardia, whereas

HR values over 100 bpm are defined as tachycardia. Higher HR values have a shorter duration of the diastole in comparison to the systole, which result in a decrease in stroke volume. In the PPG signal, the HR can be easily deduced through its AC component, which is synchronous with the heartbeat.

1.2.3 Heart Rate Variability

The HRV is a measure of the variation of beat-to-beat intervals, i.e. the cyclic fluctuation of RR-intervals, which provides more accurate information about the ANS. The RR intervals, or NN-intervals, represent the time between two successive R-waves of the QRS complex of the Electrocardiography (ECG) signal. In PPG, the R peaks are encountered in the pulsatile component, and correspond to the systole. The HRV represent the ability of the heart to change according to different scenarios. It provides indirect information about the autonomic balance, blood pressure, heart and vascular tone (Allen, 2007). There are a few time domain measures used to evaluate the HRV which quantify the amount of variability between successive heartbeats, shown in Table 1.3.

Table 1.3: Time domain measures of the HRV (adapted from Shaffer and Ginsberg, 2017).

Parameter	Unit	Description
SDNN	ms	Standard Deviation of the NN-intervals, calculated over 24 h periods
SDANN	ms	Standard Deviation of the Average NN-interval, calculated each 5 min segment of a 24 h recording
pNN50	%	Percentage of successive NN intervals that differ by more than 50 ms
RMSSD	ms	Root Mean Square of Successive Differences of NN-intervals, calculated over short periods of time

The SDNN is generally calculated for longer acquisitions and is more accurate for periods over 24 h. Nonetheless it can also be calculated over 5 min segments, and even some researchers have proposed shorter time intervals between 60 – 240 s (Salahuddin et al., 2007, Baek et al., 2015). The pNN50, which reflects the percentage of adjacent NN-intervals higher than 50 ms, usually require a 2 min segment, however some researchers have suggested shorter periods of 60 s (Baek et al., 2015). The RMSSD, which reflects the variance of each heartbeat, is the most commonly used time domain measure used to evaluate the changes reflected in HRV. Lower values of RMSSD are correlated with higher risk of sudden death in epilepsy (DeGiorgio et al., 2010).

The HRV can also be evaluated in the frequency domain, and is separated into its three main components: very low frequency (VLF), low frequency (LF), and high frequency (HF). A more detailed description of these components is shown on Table 1.4.

Table 1.4: Frequency domain measures of the HRV (adapted from Shaffer and Ginsberg, 2017).

Parameter	Unit	Description
VLF Power	ms^2	Absolute power of the VLF band (0.0033 – 0.04 Hz)
VLF Peak	Hz	Peak frequency of the VLF band (0.0033 – 0.04 Hz)
LF Power	ms^2	Absolute power of the LF band (0.04 – 0.15 Hz)
LF Peak	Hz	Peak frequency of the LF band (0.04 – 0.15 Hz)
HF Power	ms^2	Absolute power of the HF band (0.15 – 0.4 Hz)
HF Peak	Hz	Peak frequency of the HF band (0.15 – 0.4 Hz)
LF/HF Ratio	–	Ratio between LF and HF power

The absolute power of the LF and HF component can also be expressed in normal unit (n.u.), which represent the absolute power of the LF or HF band, divided by the sum of these two bands. The VLF typically requires periods of acquisition of a minimum of 5 min, but it is more accurate for longer periods of acquisition of over 24 h. The amplitude and frequency oscillations of the VLF component of the HRV are influenced by the SNS. VLF power values may be correlated to physical activity (Bernardi et al., 1996) and lower VLF power values are associated with arrhythmic death and high inflammation (Bigger Jr et al., 1992, Carney et al., 2007). The LF component is typically recorded over at least 2 min periods, and during resting conditions, this band primarily reflects the baroreceptor activity (McCraty and Shaffer, 2015). LF power is typically associated with the PNS, but may be produced by the SNS as well. Higher LF power values are associated with respiratory related activities, such as slow breathing or deep breathing, typically around 3 – 9 breaths/min. The HF band is generally recorded over at least 1 min periods and reflects the PNS activity. It is also called the respiratory band since it corresponds to the variations of the HR related to respiration (also known as RSA). The HF is usually affected by higher respiration rates, between 9 – 24 breaths/min. Lower HF power values are associated with stress and anxiety. The LF/HF ratio is generally calculated over 24 h periods and provides an estimate of the ratio between SNS and PNS activity, which mainly contribute to LF and HF power, respectively (Shaffer et al., 2014). As a result, lower LF/HF values reflects higher PNS activity (e.g. rest) and higher LF/HF values reflects sympathetic dominance (e.g. fight-or-flight response).

1.3 Meditation and Science

It is difficult to talk about meditation without mentioning yoga. Etymologically, the literal meaning of the term yoga is to bind or to unify. Similarly, the term religion follows the same principle, and its literal meaning is to reconnect. Nonetheless, yoga is not restricted to any particular religion, and it is the base of Brahmanism, which originated from the *Vedas* (1500 – 500 BCE). In fact, one the very first written evidences of meditation is found in the *Vedas*. Yoga is used for personal transformation and to alleviate the suffering that is the human condition, which connects the mind and body, the mind and consciousness and ultimately the individual consciousness with consciousness itself (Rao and Paranjpe, 2008).

One of the very first studies in meditation goes back to 1935, when Thérèse Brosse decided to bring a portable Electrocardiography (ECG) apparatus to India and measure the voluntary attempt of control of the heart rate, which was claimed by yogis (Wenger and Bagchi, 1961). The author concluded that the heart could indeed be subjected to voluntary control, since one of the ECG recordings revealed a gradual reduction in heart potentials close to zero. Many other claims stated by yogis, such as voluntary control of visceral muscles and increase in body heat, started to intrigue some researchers, and Wenger and Bagchi decided to test these claims (Wenger and Bagchi, 1961). They concluded that the voluntary control of autonomic functions of the human body was very rare amongst yogis. Since then, meditation research has come a long way, and with the improvement of medical imaging and monitoring methods it is revealing many promising results.

Many of the modern studies in meditation seem to primarily focus on the benefits of its regular practice, such as stress relief, decrease in anxiety and improvement of overall well-being. Although meditation may in fact be beneficial, these results do not contemplate the original purpose of meditation, which traditionally aims at improving concentration and cessation of suffering. Several studies failed to understand the physiological aspects of meditation and its implications (Awasthi, 2013). As stated by Goleman and Davidson, the real effect of meditation does not necessarily occur during its practice, but rather during the practitioner's normal state (Goleman and Davidson, 2018). A continued meditation practice over long periods of time will alter the traits of the mind and thus endure the effects of meditation, i.e. altered traits and state effects will take place, respectively. The altered traits can be regarded as the psychological changes of the brain in a permanent manner, whereas the state effects are simply altered states of consciousness occurring during meditation and end shortly after its practice. The beneficial results reported by many researches are no more than state effects due to meditation practice, and not in actuality altered traits of the mind. In addition, many of them also fail to mention that there may be some negative side effects as a result of meditation practices, which are important from a clinical perspective, and include depression, anxiety and depersonalization (Shapiro Jr, 1992, Kennedy, 1976).

As a result of the current misinterpretations of the fundamental philosophical aspects of meditation, research in this field is facing several difficulties regarding its definition, study design and ultimately its outcomes (Awasthi, 2013, Davidson and Kaszniak, 2015).

There is no general agreement on the definition of meditation. In fact, there is no singular definition of it. If we go back in time, according the Patanjali (400 – 300 BCE), considered the father of yoga by many, meditation is defined as the stilling of the fluctuations of the mind. However, this definition is difficult to interpret in the light of neuroscience (Bærentsen, 2015). In fact, many researchers question whether it is possible to definite meditation in scientific terms. A large number of studies refer to meditation as a wide range of practices, without any type of distinction between them (Lutz et al., 2007). In addition, there seems to be a worrying lack of distinction between the meditation practice (or technique) and the state of meditation. (Ramakrishna Rao, 2011, Lomas et al., 2015). According to the *yogasutra*, meditation is achieved when the yogi, i.e. the one that practices yoga, is able to control the fluctuations of the mind. In line with this description, meditation is regarded as a state achieved by the yogi, also called *samadhi* or *nirvana*. In addition, traditional texts also describe a panoply of techniques to reach this altered state of consciousness, which is what most publications describe. However, these papers also classified these techniques, or practices, as different meditations, which is not accurate. A simple way to understand this difference is to think of a student studying for an exam. The state that this student would like to reach is a state of concentration, but the way they reach it can vary, i.e. their study technique. In a meditation context, this state of concentration is a state of complete liberation of suffering (*samadhi*), and there are a number of different techniques to attain it, i.e. different meditation practices. Regardless of the technique that is performed, if one masters it, the ultimate state of meditation will always be the same. This is why some authors prefer to define meditation as a state of altered consciousness (Fell et al., 2010). This means that a proficient meditator is in a continuous state of meditation throughout their life, and as a result have attained an altered state of consciousness (Goleman and Davidson, 2018). Moreover, there is also a confusion with the terms mindfulness and meditation. Many authors have used these terms as synonyms, when in fact they are not. This largely contributes to the difficulty in reaching a consensus in meditation studies. In true sense, mindfulness and meditation do not mean the same. To clarify, mindfulness is a meditation practice. Also regarding the definition of mediation, some authors have proposed the categorization of meditation practices, although it seems an unattainable task (Fell et al., 2010). Authors Lutz, Dunne and Davidson have proposed the following categorization of meditation practices: focused attention (FA), open presence, or open-monitoring (OM), and non-referential compassion, or simply compassion (CMP) (Lutz et al., 2007). FA meditation practices are characterized by the employment of voluntary focus of attention on a single object in a sustained manner (Davidson and Lutz, 2008). The mind directs all its attention to one single point (e.g. breathing). These meditation practices are commonly used by novice meditators, since they help to educate the untrained mind. OM meditation practices are very different techniques. They are considered more advanced, and normally practitioners only begin their practice after being familiarized with FA meditation practices. OM techniques initially involve any kind of FA practice to help ease the mind, reduce distractions, and become aware of the state of both the mind and body. As they evolve, the practitioner enters a monitoring state, where no explicit focus on a single object is retained (Davidson and Lutz, 2008). Mindfulness refers not only to the focusing of the mind, but the awareness that keeps track of that focus in the present moment, and as such it falls into the OM category. The main goal of CMP meditation practices is to produce a specific state characterized by an intense feeling of love and kindness (Lutz et al., 2007). They are considered more advanced techniques, and involve OM aspects as well. During its practice, the practitioner can cultivate the feeling of compassion for themselves, close family members and friends, people with whom they have a difficult relationship, or to a non-referential being, while at the same time maintaining an awareness of the state of open presence. The loving-kindness meditation practice is an example of CMP meditation, in which the subject focuses on a specific living being. Given that these three general types of meditation practices are different in many aspects, it is expected that they produce different effects on both the body and mind.

According to Awasthi, the poorly designed methodologies are another concern regarding meditation research, which reflect the lack of knowledge about meditation and its implications and origins, and ultimately originate different outcomes (Awasthi, 2013). The lack of agreement in the study design makes the vast majority of meditation studies not replicable, which in turn result in an impossible validation of its outcomes. These methodological issues include the choice between conducting a cross-sectional or longitudinal study design. The first one, which may also be referred to as transverse study, analyses data from a given population at a specific time. In the context of meditation, an example of a cross-sectional study is the comparison between expert meditators and non-meditators at an anatomical, physical or psychological level. On the other hand, longitudinal studies measure continuous and repeatedly the same variables of particular individuals over usually long periods of time. In the context of meditation, a longitudinal study accompanies the progresses of non-meditators over the course of a few weeks, for example. In such case, the researcher would analyse pre- and post-meditation intervention data and compare its changes over time. Both these study designs have their own advantages and disadvantages. In a longitudinal study, the major difficulty is to find willing participants that meet all requirements and perform all requested tasks for that specific time. In addition, the problem with a cross-sectional study design is determining the experience of the participants. Obviously, non-meditators are easy to find, since they require participants with no previous experience with meditation, however the picture gets a little bit more complicated when trying to differentiate between experienced, intermediate and novice meditation practitioners. This experience, or inexperience, can be determined whether in years or the total number of hours of meditation practice. Lomas et al. provide a description of the different criteria used in several studies to determine the experience of the participants, in which the range of experienced meditators varies between 1-9 years and 40-1740 hours (Lomas et al., 2015). Clearly this classification is very different and it is not surprising that different results and conclusions arise. The meditation experience translated in the number of hours seems to be a more accurate approach, however there is no guideline to calculate such metric. And this becomes even more troublesome when other parameters such as formal and informal meditation practices are introduced. The formal meditation practice specifies the intentional commitment of time to perform a given technique. For example, the practice of a meditation technique every morning for 30 min. The informal meditation practice is the adaption of formal meditation practices in everyday situations, which has the purpose to bring awareness to the present moment. As a result, the experience one has in meditation cannot simply be attributed to its formal practice. However, it is even harder to account for this type of experience throughout time, since it does not have a rigorous schedule like the formal practice. In addition, the number of hours spent in meditation retreats also plays an important role in the experience of meditation practice, and should be accounted for when calculating the meditator level experience (Wielgosz et al., 2016).

The objective analysis of meditation practices is not a simple task. According to Varela and Shear, researchers should include three measures of meditation practice to ensure a robust analysis: first-, second-, and third-person perspectives (Varela and Shear, 1999). The first-person perspective is a subjective measure of the experience of the meditation practice by the practitioners themselves, which may be obtained through questionnaires. The second-person perspective is a subjective measure of the meditation practice by the teacher or master, i.e. someone familiar with the meditation practice and who is accompanying the practitioner's meditation journey. Finally, the third-person perspective is the only objective measure of the meditation itself. It is accomplished using an EEG, ECG, or any other monitoring device or imaging method. Most studies only rely on first- and third-person measures, however the first one, i.e. self-report measures, lack scientific validity as they may be biased. According to Davidson and Kaszniak, meditation research also deals with the impossibility in conducting a double-blind placebo-controlled study design and control condition (Davidson and Kaszniak, 2015). This is not possible within meditation study design methods, and the participants know the nature of the research from the start, and for that reason know what they are being evaluated for, i.e. their meditation ability. In addition, finding the adequate control condition represents a troublesome factor. It has not yet been reached a consensus regarding to what the control condition should be. In scientific studies, the control condition should be a similar technique that matches the meditation practice. However, such condition is a very difficult one to develop.

Ultimately, all of the issues mentioned above result in the amount of variability in published outcomes, and more specifically the validity of them. Due to the discrepancies in the definition of meditation and study design, most of the published papers are not replicable, which in the end makes it impossible to validate such results. A problem surrounding not only meditation research, but all research in general, is that researchers tend to not publish bad results, i.e. results that do not meet the initial hypothesis. Nonetheless, a bad or unexpected result is still a result, and in fact can help guide future research (Goleman and Davidson, 2018).

As already mentioned, a consensus on meditation research has not yet been reached, however there have been reported two main effects: relaxation response (and tonic alertness) and phasic alertness (Amihai and Kozhevnikov, 2015). The relaxation response, which was named by Benson, occurs due to a decrease in sympathetic activity, or to an increase in parasympathetic activity, and is found in transcendental and mindfulness meditation practices (Benson et al., 1975). The relaxation response was later termed as a state of tonic alertness, which is a vigilant yet relaxed state. In fact, interpreting meditation as a relaxation technique has led to a number of consequences and has been criticised by several authors (Boals, 1978). If meditation is the same as a relaxation technique, what differentiates it from another relaxation technique? In fact Benson concluded that there is no difference between meditation and other relaxation techniques, they are just different stimuli to achieve the same relaxation response. However, this interpretation does not even go in line with the original purpose of meditation, and interestingly enough, traditionally relaxation can pose as an obstacle to meditation. Besides, the relaxation response does not explain the controversial effects sometimes reported after extensive meditation practice. Since Benson's proposal of meditation as a relaxation response, several other studies have found contradictory results. Meditation practices according to Vajrayana tradition arise a state of arousal, more specifically a state of phasic alertness, which is characterized by the activation of SNS, contrarily to Mahayana and Theravada meditation traditions exhibit a relaxation response (Amihai and Kozhevnikov, 2015).

In terms of the electrophysiological activity and the neurophysiology of meditation, there is great number of studies reporting mixed outcomes in EEG oscillations, including increases, decreases and no differences (Fell et al., 2010, Lomas et al., 2015, Travis and Shear, 2010). According to Fell et al., meditation practices induces altered states of consciousness which should be accompanied with an altered neurophysiological state, and as a result should be quantitatively measurable (Fell et al., 2010). These altered states can be either transient or permanent, which meet with the same ideals proposed by Goleman and Davidson of state effects and altered traits (Goleman and Davidson, 2018). Fell et al. hypothesised that every meditation training, regardless of its tradition or practice, goes through a similar process of development. The first and second stages, which concern the physical demands (such as posture) and internalized attention are common aspects in every meditation journey, and characterize the beginner level. The third stage of the process is the correct performance of the meditation technique, and is already considered an advanced level of meditation. However, it is not yet an altered trait of consciousness. This altered trait of consciousness is only attained by expert meditators, and is called *nirvana* or *samadhi*. In terms of electrophysiological aspects, the beginner level of meditation include the increase in power and synchronisation of low frequency activity, such as alpha and theta. The expert level of meditation includes the beginner level features as well as an increase of power and synchronisation of gamma activity. Alpha synchronization seems to be independent of the meditation practice, and is commonly referred to one of the first signatures of meditation ability. However, it is one of the most easily controlled brain rhythm, and as such it is not exclusive of or even due to meditation practice. On another review article, Lomas et al. mention the most common findings occurring during mindfulness in comparison to a resting eyes-closed condition (control) (Lomas et al., 2015). The authors reported that the three most common results were greater amplitude in alpha, theta and beta bandwidth oscillation. The least common finding was delta oscillation, and the gamma amplitude was associated with years of practice, which agrees with the theory that only expert meditators exhibit activity in this rhythm. The presence of alpha and theta oscillations are characteristic of a relaxed, yet alert, state. Their presence may represent the increase in attention, and more specifically, internalized attention due to the presence of the alpha rhythm. According to Fell et al., this combination would represent one of the first basic changes, or even state effects, of the meditation process. Travis and Shear summarized the neurophysiological effects during meditation practices, according to the following categories: FA, OM and automatic self-transcending (Travis and Shear, 2010). The EEG bands related to FA practices are mainly gamma and beta, while the OM meditation practices exhibits a higher theta power and the automatic self-transcending meditation practices shows an increase in alpha power. It is relevant to mention that accordingly to this categorization, the authors considered the loving-kindness compassion meditation practice as being apart from the FA category. In this case, the mind is directing all its focus to a single point, however, it is also generating an intense feeling of love and kindness, which certainly is much different than simply focusing attention on the breath. In fact, the more suitable category for this meditation practice would be the CMP meditation, in particular loving-kindness meditation practice. This illustrates the many misinterpretations that can arise due to the non-existence of a suitable and consensual categorization for meditation practices.

Ferrarelli et al. investigated the electrical activity of the brain in long-term meditators during sleep, in practitioners of FA, OM and loving-kindness meditation practices (Ferrarelli et al., 2013). The authors used high-density EEG during sleep and compared long-term meditators to naïve meditators. The long-term meditators and naïve meditators exhibited no differences in rapid eye movement sleep gamma power. However, the long-term meditators showed an increase in parietal-occipital EEG gamma power during non-rapid eye movement sleep, which was correlated with the extent of meditation practice. This is a very unique and interesting study that demonstrates that meditation does not only have an impact during its practice, but that extends to other aspects of the lives of its practitioners. In another study, Lutz et al. reported that long-term meditators self-induced sustained high-amplitude gamma oscillations and phase synchrony during loving-kindness meditation practice (Lutz et al., 2004). Moreover, during the baseline long-term meditators exhibited higher gamma activity to slow oscillatory activity ratio. This ratio increased during the meditation period, and was higher in the post-meditation than in the baseline period.

Only a few studies have focused on the changes of the heart during meditation practice (Lumma et al., 2015, Phongsuphap et al., 2008, Léonard et al., 2019). Lumma et al. studied the effects in the cognitive and emotional processes of different types of meditation practices during formal practice (Lumma et al., 2015). Some meditation practices require greater attentional, cognitive and emotional processes, while others produce relaxation. This study reported different HR and HRV measures in different types of meditation. A breathing type of meditation produces lower HR, making it a suitable technique for people that deal with anxiety. On the other hand, loving-kindness and observing thoughts meditation practices produce an increase in HR. For this reason, people with anxiety or heart-related issues will not benefit from these types of meditation practices. Phongsuphapap et al. studied the effects in HRV during concentrative meditation and concluded that the *samadhi* state is characterized by a resonant peak (Phongsuphap et al., 2008). This resonant peak could be of different types, and each one produces different effects on the body, such as sympathetic or parasympathetic modulation and baroreflex sensitivity. Léonard et al. investigated the effects on HRV of regular heartfulness meditation practice during rest, control and meditation conditions (Léonard et al., 2019). The control task consisted in a rhythmic respiration, i.e. a paced breathing exercise given by an auditory signal. During the meditation period, it was observed a reduction in HRV. These findings suggest the suppression of global vagal modulation and increase of sympathetic modulation, in comparison to rest and control periods. As a curiosity, according to Yogic traditions, the paced breathing exercise could be referred to as *pranayama*, which is the control of the breathing. It is somewhat a breathing type of meditation, which according to Lumma et al. is a less effortful meditation practice, and therefore, require less cognitive processes, and thus suppression, i.e. decrease, of sympathetic modulation. Amihai and Kozhevnikov compared neurophysiological signals of EEG and ECG and cognitive correlates of meditation practices from Theravada and Vajrayana traditions and concluded that different practices produce different effects on the body, i.e. relaxation or arousal (Amihai and Kozhevnikov, 2014).

Two very interesting studies investigated the respiration and breathing measures during meditation (Levinson et al., 2014, Wielgosz et al., 2016). According to Levinson et al., there is a lack of reliable measures of mindfulness meditation, and as such propose a valid behavioural measure of breath counting (Levinson et al., 2014). They concluded that breath counting was a reliable measure, and is associated with less mind wandering. Wielgosz et al. compared the effects of mindfulness meditation on respiration rate on long-term meditators in comparison to non-meditators (control group) (Wielgosz et al., 2016). The authors hypothesised that mindfulness meditation should have lower respiration rate during its practice and baseline. The results showed that during the baseline condition, long-term meditators exhibited in average a lower respiration rate by 1.6 breaths/min in comparison to the control group. They also found that the respiration rate is associated with practice experience, and even more so with retreat hours.

Finally, Ahani et al. have successively come up with an objective measure of meditation ability, by means of EEG and respiration signals (Ahani et al., 2014). A support vector machine classifier with both EEG and respiration signals proved to be an accurate measure to distinguish meditation and control tasks, rather than EEG or respiration signals alone.

To summarize, researchers in the field of meditation should aim at more rigorous definition and study designs. Meditation has been around way before scientific reports, so perhaps to clarify its study, science should find a way to include its traditions, practices and origins in its interpretations. It should be the researcher's job to learn more about meditation in order to understand it. The study of meditation cannot be done simply with scientific tools, since it also includes semantic, linguistic, philosophical and even historical aspects that influence its whole practice.

1.4 Objectives

The growth in interest in meditation research, and even in its practice by occidental societies, has led to the conception of this study. Because there is a major hype around this topic, it is even more so important to understand its implications and effects, whether short- or long-term. Thus, the main goals of this study are to compare the physiological differences between non-meditators and meditators, during a relaxation period (baseline), meditation task and final relaxation period, the differences between three different practices of meditation, and finally the differences between a daily and regular practice of meditation. In order to do so, EEG and PPG signals were acquired.

Chapter 2

Methodology

2.1 Data Acquisition

2.1.1 Categorization of Meditation Practices

This study contains meditation practices from different backgrounds, which are divided into three main categories: FA, OM and CMP. Meditation practices which were characterized by the voluntary sustained focus of attention on a single object, or point, were integrated in the FA category. The OM category includes practices which may include an initial FA meditation practice, to help ease the mind and reduce distractions, but ultimately evolves to a non-sustained focus of attention on any particular object, i.e. the practitioner enters a monitoring state and is attentive to more than one single point. Practices which were characterized by the cultivation of an intense feeling of compassion, love or kindness, whether towards themselves, others, or non-specific beings, were incorporated in the CMP category.

2.1.2 Description of Participants

The experimental group included a total of 19 participants, which were divided into two distinct groups: meditators and non-meditators, i.e. the control group. The demographic and meditation practice characteristics of both groups are shown in Table 2.1.

Ten meditators (with ages between 34 and 58 years, years of meditation practice between 2 and 21, duration of meditation practice between 10 and 90 min, total experience in meditation between 304 and 7665 h, number of retreats between 0 and 30) fulfilled a questionnaire found in Appendix A. Subjects with a regular or daily practice of meditation, for a total of at least 300 hours were selected for this group. Participants with a daily practice of meditation performed every day of the week (i.e. 7 days/week) whereas a regular practice was performed between 3–4 days/week. Four of the meditation practitioners followed the teachings of Yoga, two of Mahayana, one of Vajrayana, one of Zazen, one of White Plum Asanga and one did not follow any particular teachings.

The control groups included 9 non-meditators (aged between 21 and 61 years) which were selected

Table 2.1: Characterization of the meditator and control groups. The values represented are the average ± standard deviation. F = Female, M = Male, D = Daily, R = Regular, Y = Yes, N = No, FA = Focused Attention, OM = Open-Monitoring and CMP = Compassion.

Group	Meditator	Control	
		EEG	PPG
Age	46.1 ± 8.7	40.8 ± 17.7	37.1 ± 17.5
Gender (F/M)	6/4	5/4	6/3
Frequency of Practice (D/R)	6/4	-	-
Guidance of Practice (Y/N)	4/6	-	-
Years of Practice	10.0 ± 6.8	-	-
Duration of Practice (min)	34.0 ± 24.8	-	-
Total Experience of Practice (h)	1587.9 ± 2814.8	-	-
No. Meditation Retreats	8.9 ± 10.1	-	-
Meditation Practice (FA/OM/CMP)	4/4/2	9/0/0	9/0/0

via personal interviews. Subjects from this group did not have any previous meditation experience, however they declared an interest in its practice. This group had to be divided into two subgroups because it contained two participants on prescribed medications, specifically for heart attack and anxiety. For this reason, the subject with cardiac problems was excluded from the PPG analysis, and the subject on psychotropic medication was excluded from the EEG analysis. However, they were included in the EEG and PPG subgroup, respectively.

2.1.3 Acquisition Procedure

This project used the BrainBIT headband, developed at *Instituto de Biofísica e Engenharia Biomédica* (IBEB) of the Faculty of Sciences of the University of Lisbon (Batista et al., 2019). The headband uses the multimodal platform BITalino (r)evolution. It has two pairs of frontal electrodes and one earlobe sensor, which respectively acquire EEG and PPG signals in simultaneous manner (Figure 2.1). The two EEG sensors are placed on the forehead in Fp1 and Fp2 locations of the standard 10-20 system.

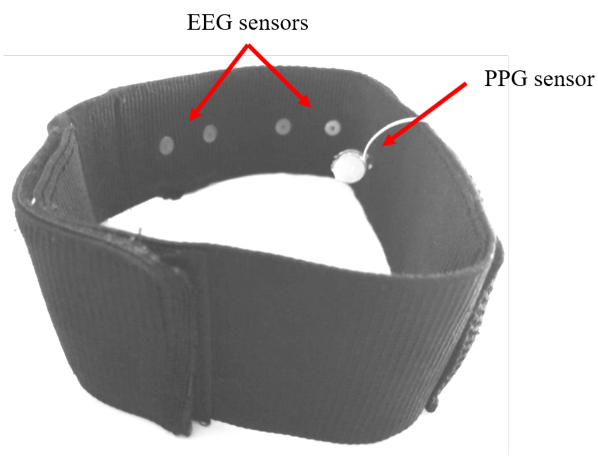


Figure 2.1: The BrainBIT headband.

The mobile application BitadroidR[1] was used to record these physiological signals. The application communicated with the wearable headband via Bluetooth. A configuration on the mobile application was set for the signal's acquisition prior to the recordings. Channels A1, A2 and A3 were selected for the recording with EEG, EEG and ECG name tags, respectively. The A1 and A2 channels corresponded to the Fp1 and Fp2 electrode locations, indicating the left and right prefrontal hemispheres, respectively. The sampling rate was 100 Hz, and the visualization rate was 10 Hz. A series of screenshots of the interface of the application are shown in Figure 2.2.

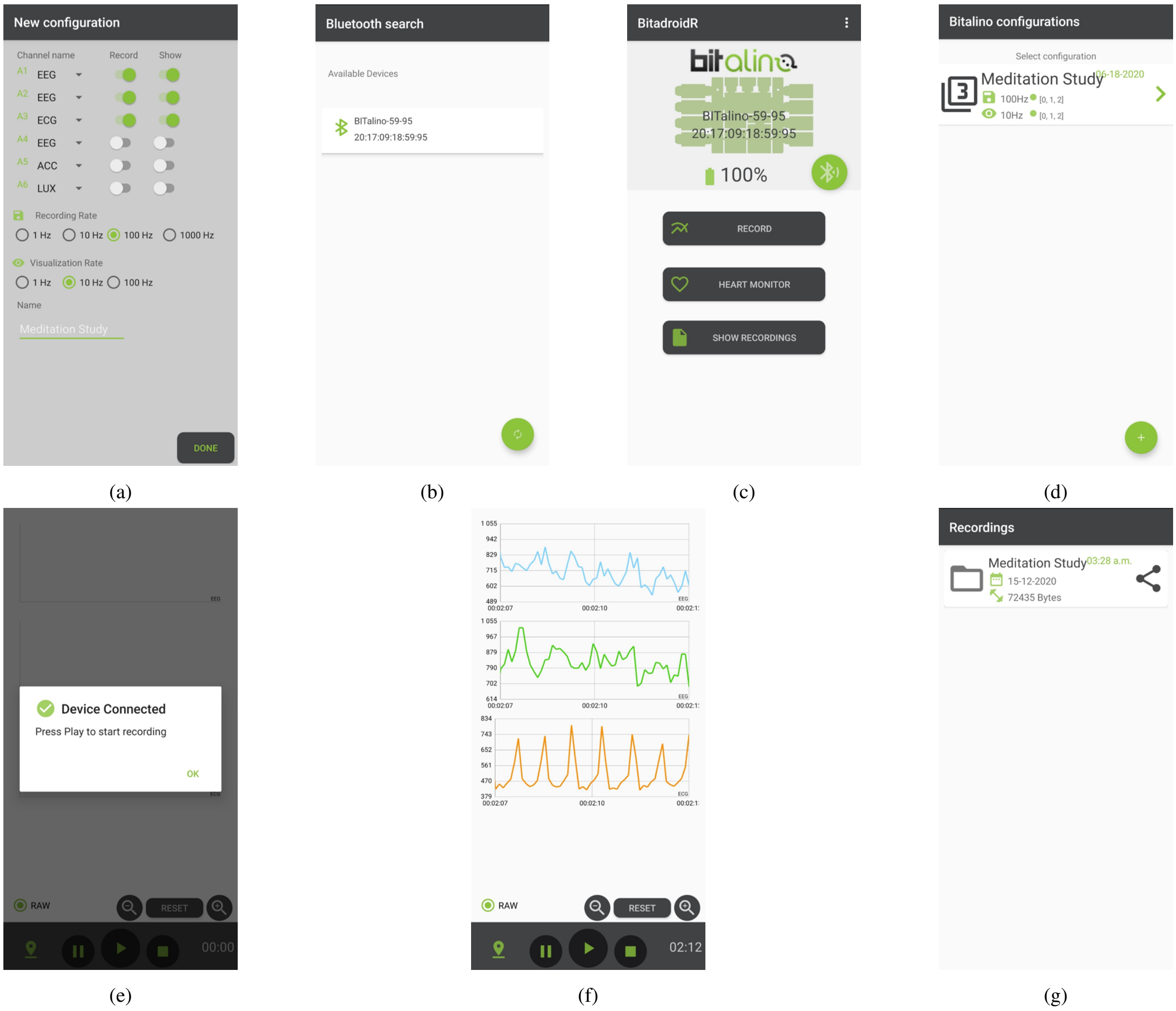


Figure 2.2: (a) Configuration of the acquisition parameters; (b) Search for Bluetooth devices and selection of device corresponding to BrainBIT; (c) The application interface in which to begin acquisition simply press the RECORD button; (d) Select the configuration to start the acquisition; (e) To start the acquisition press the PLAY button; (f) The EEG and PPG signals with a delay of 0.1 s; (g) The saved data from the acquisition.

Participants from both groups performed three tasks: baseline, meditation and post-meditation. During all of these tasks, participants were wearing the BrainBIT headband around their forehead and the ear sensor clipped to the left earlobe.

For the baseline task, participants were instructed to sit in a comfortable position and close their eyes for 2 min. During this period, participants were instructed to remain in a relaxed state, and meditators

[1] https://github.com/DavidGMarquez/BitadroidR

were expressly asked to endure a non-meditative state. At the sound of a bell, participants began the meditation task, with a duration of 10 min. Participants from the meditator group were previously instructed to perform their regular meditation practice and participants from the control group were asked to perform a breathing meditation practice, which was instructed prior to the acquisition (Appendix A). The meditation task ended with the sound of three bells, and participants begun the post-meditation task. This task had the same instructions and duration of the baseline task. A scheme of the acquisition procedure is shown in Figure 2.3.

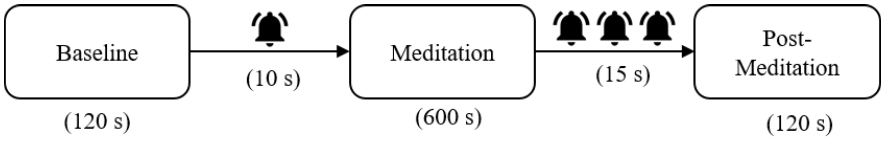


Figure 2.3: Scheme of the acquisition procedure

2.2 Signal Processing

The EEG and PPG signals were processed using MATLAB R2018a (version 9.4.0.813654).

Before describing the signal processing steps, it is necessary to introduce a brief explanation of the Wavelet Transform (WT), in particular the Continuous Wavelet Transform (CWT) and the Discrete Wavelet Transform (DWT). When analysing physiological signals, it is necessary to keep in mind that most of them are non-stationary signals. This means that their characteristics change with time. Although the Fast Fourier Transform (FFT), which transforms time domain features into the frequency domain, is an efficient computational tool widely used by other researchers, it assumes that the signal is stationary. Therefore, it is not applicable for physiological signals such as the EEG. The WT is a much more efficient method for the analysis of non-stationary signals. It allows the time-frequency analysis of the signal, and for that reason it is very useful for biomedical signal processing.

2.2.1 Continuous Wavelet Transform

The CWT of the signal $f(t)$ is defined as the integral of the signal multiplied by the scaled shifted versions of the wavelet function $\psi(t)$, as shown in Equation 2.1.

$$CWT(a,b) = \int_{-\infty}^{+\infty} f(t) \frac{1}{\sqrt{|a|}} \psi(\frac{t-b}{a}) dt \tag{2.1}$$

where a and b are the scaling and time shifting parameters, respectively. However, calculating the wavelet coefficients at every scale is a very time consuming and computationally expensive method. The DWT provides much more efficient and less complex method than the CWT.

2.2.2 Discrete Wavelet Transform

The DWT of the signal $f(t)$ is defined as integral of the signal multiplied by the power of 2 of the scaled shifted versions of the wavelet function $\psi(t)$, as shown in Equation 2.2.

$$DWT(j,k) = \frac{1}{\sqrt{|2^j|}} \int_{-\infty}^{+\infty} f(t)\psi(\frac{t-2^j k}{2^j})dt \tag{2.2}$$

where a and b are replaced by the scales and positions 2^j and$2^j k$, respectively. The DWT uses two types of filters: low-pass filter (LPF) and high-pass filter (HPF). The DWT is a combination of filtering and down-sampling, in which the input signal passes through a LPF and HPF and is down-sampled by a factor of 2. This process is repeated until the frequency range of interest is obtained. The number of times this process is performed is called the decomposition level. The maximum level of decomposition is $\log_2(N)$, where N is the length of the input signal. For the reconstruction step, the same process is applied, however the down-sampling is replaced with up-sampling by a factor of 2 and zero-padding. Each level of decomposition is composed by detail coefficients (cD) and approximate coefficients (cA), as shown in Figure 2.4.

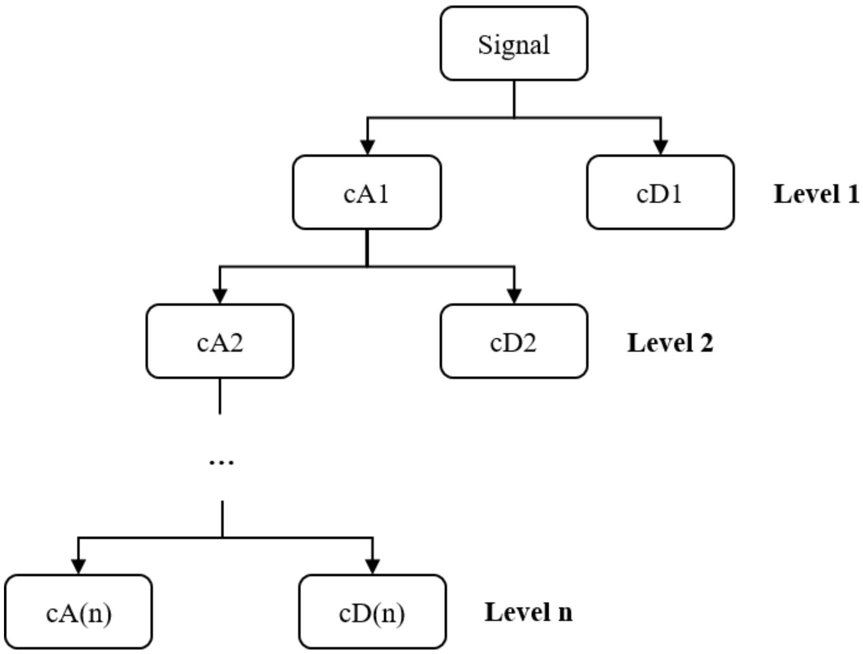


Figure 2.4: Levels of decomposition of the DWT.

The cD is obtained from the HPF whereas the cA is obtained from the LPF. The cD are associated with the wavelet function and capture high-frequency information (and cA capture low frequency information), providing an indication of the location of important details in the data. The important frequencies of the data may be identified when the cD shows oscillations around these frequencies.

2.2.3 EEG Signal Processing

2.2.3.1 Filtering and Artefact Correction

The EEG signals are often corrupted by physiological artefacts, such as muscle, eye and cardiac activity, and external artefacts, such as power line interference at 50 or 60 Hz. The latter can be easily removed by simple filtering techniques, whereas the physiologic artefacts require a finer processing. Generally, the physiologic artefacts are in the same frequency range as other important EEG signal components and may be confused with neuronal rhythms. A simple way to address these artefacts is simply artefact rejection, i.e. rejection of epochs contaminated with artefacts. However, besides being a very time consuming approach, it results in a considerable loss of available data. The EEG contamination can be represented as shown on Equation.

$$EEG_{recorded}(t) = EEG_{true}(t) + k \cdot EOG(t) + s \cdot EMG(t) + u \cdot ECG(t) \tag{2.3}$$

where $EEG_{recorded}(t)$ is the recorded contaminated EEG signal, $EEG_{true}(t)$ is the EEG that represent the cortical activity, $k \cdot EOG(t)$ is the propagated ocular artefacts (OA) due to eye blinks and eye movements, $s \cdot EMG(t)$ is the propagated muscular artefacts due to eye blinks, jaw clenching and swallowing, and $u \cdot ECG(t)$ is the propagated cardiac artefacts. The $EEG_{true}(t)$ can be estimated by efficiently removing the unwanted artefacts $k \cdot EOG(t)$, $s \cdot EMG(t)$ and $u \cdot ECG(t)$. These last two artefacts can be addressed by using filtering techniques, such as low-pass filters to remove higher frequencies (i.e. muscle activity is usually between 20-–300 Hz), and high-pass filters to remove lower frequencies (i.e. cardiac activity is usually between 1–2 Hz). The WT is a powerful and promising technique for artefact removal of a single EEG channel (Khatun et al., 2016).

In this study, the DWT denoising approach is used to eliminate the OA, such as eye blinks and eye ball movements. The adequate choice of the mother wavelet is crucial and it should resemble to the shape of OAs. Contrarily to filtering methods, the DWT technique tends to preserve the characteristics of the signal while reducing its noise. The algorithm proposed in this study is composed by the following steps (Khatun et al., 2016):

1. Application of a band-pass filter to smooth the EEG signal;
2. Application of the DWT to the filtered yet contaminated EEG signal;
3. Identification of OA in the detail coefficients using Statistical Threshold (ST);
4. Set detail coefficient to zero where its value is higher than the ST (or lower than the negative value of the ST);
5. Reconstruction of the signal by adding up all detail coefficients.

In order to correct these artefacts, the raw EEG signal was first filtered with a 4th order Butterworth filter between 1 and 40 Hz. This step was executed using the MATLAB `butter` function to create the bandpass filter and the `filtfilt` function to perform a zero-phase digital filtering. Since the high-cut of the bandpass filter was 40 Hz, it was not necessary to implement a Notch filter to remove the 50 Hz power line interference. Afterwards, a DWT with decomposition level 8 and mother wavelet Coiflet 3 (coif3) was applied to the filtered EEG signal (Khatun et al., 2016). This mother wavelet was chosen since it resembles the most with the shape of the eye blink artifact (Krishnaveni et al., 2006).This was achieved by using the MATLAB `wavedec` function to perform the discrete wavelet transform and the `wrcoef` function to reconstruct the coefficients vector. The results of the detail and approximation coefficients of the DWT for a sampling rate of 100 Hz are shown in Table 2.2.

Table 2.2: Levels of Decomposition of the DWT, for the sampling frequency of 100 Hz.

Decomposition Level	Frequency (Hz)	Decomposed Signal
1	25.00 – 50.00	cD1
2	12.50 – 25.00	cD2
3	6.25 – 12.50	cD3
4	3.13 – 6.25	cD4
5	1.56 – 3.13	cD5
6	0.78 – 1.56	cD6
7	0.39 – 0.78	cD7
8	0.20 – 0.39	cD8
8	0.00 – 0.20	cA8

The OAs occur within the range of 0 to 16 Hz, and for this reason, only the detail coefficients bellow this value were selected for further analysis, i.e. between cD3 and cD8. For thresholding each detail coefficient, the ST metric was applied, according to Equation 2.4 (Krishnaveni et al., 2004).

$$T_k = 1.5 \times std(H_k) \tag{2.4}$$

where T_k is the threshold value at the kth level, and $std(H_k)$ is the standard deviation of the detail coefficient at the kth level. Then, the values of detail coefficient at the kth level higher than T_k or lower than $-T_k$ were set to zero. To obtain the corrected EEG signal, i.e. the artefact free EEG signal, all of the detail coefficients and approximation coefficient were summed.

However, EEG signals may also be exposed to other external artefacts, such as clipping artefacts. The EEG clipping is an artefact caused by the excess output voltage overloading the amplifiers which results in a distortion of the signal, making it appear with a flat top (Kane et al., 2017). Hence, EEG segments containing this type of artefact should be excluded from analysis. In order to address this problem, the raw EEG signal was divided into 1 s epochs, using the MATLAB `buffer` function. Afterwards, each epoch was subjected to a function that detected clipping events, i.e. saturation periods. The criteria used to detect a clipping event was the presence of more than 10 consecutive points higher (or lower) than 490 arbitrary units (a.u.) (or -490 a.u.) (Dincklage et al., 2020). This threshold was chosen after visualization inspection of every signal. If the criteria was met, the column index of the epoch was stored in an array, for later use.

After the wavelet denoising, the corrected EEG signal was divided into 1 s epochs, using the MATLAB `buffer` function as well. Afterwards, the epochs corresponding to the clipping events were set to zero, in order to preserve the total length of the time analysis (so it was not necessary to make conversions). Later, the epoched EEG signal was reshaped to a column vector, using the MATLAB function `reshape`. For further analysis, the time periods regarding baseline, meditation and post-meditation periods were selected. Since there were two transition periods, i.e. the sound of a bell, between the baseline and meditation periods and between the meditation and post-meditation periods, the 5 s prior to the beginning of the bell and the 5 s proceeding the end of the bell were excluded from analysis. The total period of acquisition was 840 s, and the sampling rate was 100 Hz, corresponding to a total of 84000 points. Each task segment was stored in a cell to simplify the following steps. The MATLAB `nonzeros` function was used to exclude the epochs containing the clipping events.

2.2.3.2 Band Extraction and Measures

The extraction of the EEG bands was accomplished using the CWT, by means of the MATLAB `cwt` and `icwt` functions. Although the CWT is a computationally expensive method, it allows the extraction of each EEG band between specific frequency ranges. The mother wavelet chosen for this study was the Morlet wavelet, since it is the one that resembles the most with physiological signals. The CWT was applied separately to each period of the EEG, and the five bands were obtained by applying the inverse CWT over the specific frequency range of each band. The frequency ranges of each EEG band used in this study were the following: delta (1 – 4 Hz), theta (4 – 8 Hz), alpha (8 – 12 Hz), beta (12 – 30 Hz) and gamma ($>$ 30 Hz). However, the MATLAB `cwt` function only returns a frequency vector with the maximum frequency of 36.8 Hz. As a result, the gamma band is specified between 30 – 36.8 Hz.

The absolute power in each period was calculated as the average of the squared values of each band. The relative power was calculated as the absolute power of each EEG band, i.e. total power, divided by the summation of all the absolute powers. The relative power of each band evaluated over time may provide an indicator for shifts in brain function. Besides the absolute and relative power of each EEG band, the following measures were also calculated:

$$ratio_{beta/(alpha+theta)} = \frac{beta}{alpha+theta} \tag{2.5}$$

$$ratio_{theta/beta} = \frac{theta}{beta} \tag{2.6}$$

$$ratio_{alpha/beta} = \frac{alpha}{beta} \tag{2.7}$$

$$arousal = \log\left(alpha_{right}\right) + \log\left(alpha_{left}\right) \tag{2.8}$$

$$valence = \log\left(alpha_{left}\right) - \log\left(alpha_{right}\right) \tag{2.9}$$

The beta/(alpha + theta) ratio is also called the engagement index, and has been used to study task engagement and mental effort (Rojas et al., 2020,Mikulka et al., 2002). The theta/beta ratio was initially considered a marker of arousal deficit, however researchers have shown that this ratio is in fact involved in executive cognitive or attentional tasks in healthy subjects, and is a potential biomarker for attentional control (Clarke et al., 2019, Putman et al., 2014). The alpha/beta ratio is used to relate the two most relevant frequency bands of the EEG signal, and allows the study of the evolution of the cognitive state (Liu et al., 2013, Jap et al., 2009). The log($alpha_{right}$) + log($alpha_{left}$) is called arousal, i.e. intensity of emotion or level activation, and has been correlated with occipital and frontal alpha activity (Barry et al., 2020, Rocha, 2017). The log($alpha_{left}$) – log($alpha_{right}$) is called valence, i.e. pleasantness of emotion, and is a frontal alpha asymmetry measure, which is used to understand emotional and affective processing (Sutton and Davidson, 1997, Rocha, 2017)). A greater left frontal asymmetry is a psychological and physiological measure of well-being (Urry et al., 2004, Davidson et al., 2003). Positive values of this measure indicate a greater alpha right power, therefore greater activity in the left hemisphere, and vice-versa (Davidson, 1992).

2.2.4 PPG Signal Processing

2.2.4.1 Time Domain Analysis

The raw PPG signal was filtered with a 5^{th} order Butterworth low-pass filter with cut-off frequency of 3 Hz. This step was executed using the MATLAB `butter` function to create the low-pass filter and the `filtfilt` function to perform a zero-phase digital filtering. Since the cut-off frequency is 3 Hz, it was not necessary to implement a Notch filter to remove the 50 Hz power line interference. The baseline, meditation and post-meditation periods were extracted in the same time intervals as the EEG signal. The R-peaks of the PPG signal were detected using the MATLAB function `findpeaks` with a minimum peak distance of 50 points and minimum peak prominence of 5. This criteria was chosen after visual inspection of all signals and was used for all participants, except for 3 subjects, in which the minimum peak prominence specification was removed. The RR-intervals (or NN-intervals, which are the corrected RR-intervals, i.e. the RR-intervals that represent normal cardiac timing and are free from artefact) were calculated by subtracting the current R-peak index with the previous one, i.e. differences between adjacent R-peaks. This step was accomplished using the MATLAB `diff` function. The HR overtime was calculated by multiplying the sampling frequency (100 Hz) by 60 (seconds) and dividing by the RR-intervals array. The minimum and maximum HR overtime values were calculated using the MATLAB `min` and `max` functions. The average RR-interval was calculated as the average value of the RR-intervals array, using the MATLAB `mean` function. The SDNN was calculated as the standard deviation of the RR-intervals, using the MATLAB `std` function. The average HR was calculated as the average of the $HR_{overtime}$ array, using the MATLAB `mean` function. The RMSSD was calculated as the square root of the average power differences between adjacent RR-intervals, using the MATLAB `std` and `diff` functions. Finally, the pNN50 was calculated as the summatory of the absolute differences between adjacent RR-intervals which were higher than 5, divided by the total length of the RR-intervals and multiplied by 100, using the MATLAB functions `sum`, `abs` and `diff`.

2.2.4.2 Frequency Domain Analysis

In order to acquire information in the frequency domain, the RR-intervals (which correspond to the HRV) were interpolated using the MATLAB function `spline`, and down-sampled to 4 Hz (Nayan et al., 2018). Afterwards, the frequency measures of the HRV such as the VLF, LF and HF power were calculated. To extract the frequency values of each component, the MATLAB function `plomb` was used, and the `trapz` function was used to calculate the trapezoidal numerical integration. The VLF, LF and HF peaks were also extracted by retrieving the index of the maximum value of the Power Spectral Density (PSD) in each band. The BR value was calculated the same way as the VLF, LF and HF peaks, between the frequency range of 0.1 and 0.5 Hz, i.e. between 6 and 30 breaths/min.

2.3 Statistical Analysis

To perform the statistical analysis, the SPSS software (version 26.0.0.0) was used. The statistical analysis used for this study was conducted using non-parametric tests, due to the small sample size. These tests do not assume that the data comes from any specific distribution (e.g. normal distribution), and can be used for both quantitative and qualitative data.

The Mann-Whitney test was used to compare the differences between the meditator and control groups during the baseline, meditation and post-meditation periods . For each group, the Friedman test was applied to compare the differences between all three periods. The Wilcoxon test was also used to compare two paired periods of each group, i.e. baseline vs. meditation, meditation vs. post-meditation and baseline vs. post-meditation.

The Kruskal-Wallis test was used to compare the differences between all three meditation practices during baseline, meditation and post-meditation periods. To compare paired meditation practices during each period, the Mann-Whitney test was used, i.e. FA vs. OM, OM vs. CMP and FA vs. CMP.

To conclude, the Mann-Whitney test was applied to compare the differences between the daily and regular practices of meditation during baseline, meditation and post-meditation periods.

Chapter 3

Results

The results were divided into three different analysis: comparison between groups, comparison between meditation practices and comparison between frequency of practice. Firstly, the results between the EEG and PPG signals differences between meditators and control is presented. Secondly, and regarding only the meditator group, it is presented a comparison between the three different practices of meditation, i.e. comparison between FA, OM and CMP. Finally, and concerning the meditator group as well, a comparison between the frequency of meditation practice is presented, i.e. comparison between the daily and regular practice of meditation.

3.1 EEG Pre-Processing

This section provides the results obtained during the pre-processing stage of the EEG signals, such as the detection of the clipping events and the correction of the OAs. Overall, the percentage of valid data for further acquisition after removal clipping events is shown in Table 3.1.

Table 3.1: Percentage of available data in each period, after detection of clipping events.

Group	**Baseline (%)**	**Meditation (%)**	**Post-Meditation (%)**
Meditator	94.8	98.7	98.9
Control	96.9	99.5	99.9

An example of clipping events is demonstrated in Figure 3.1.

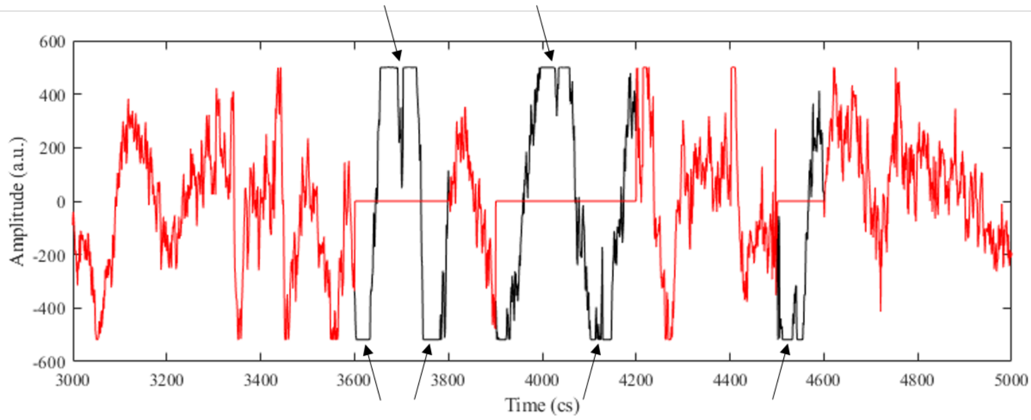


Figure 3.1: Detection of the clipping events, i.e. periods of saturation. The black line represents the raw EEG signal and the red line represents the EEG signal with epochs containing clipping events set to zero. The black arrows represent the clipping events.

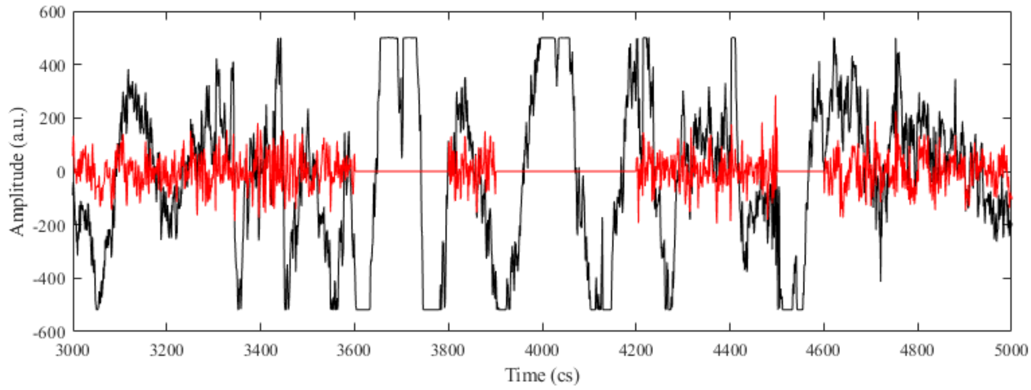
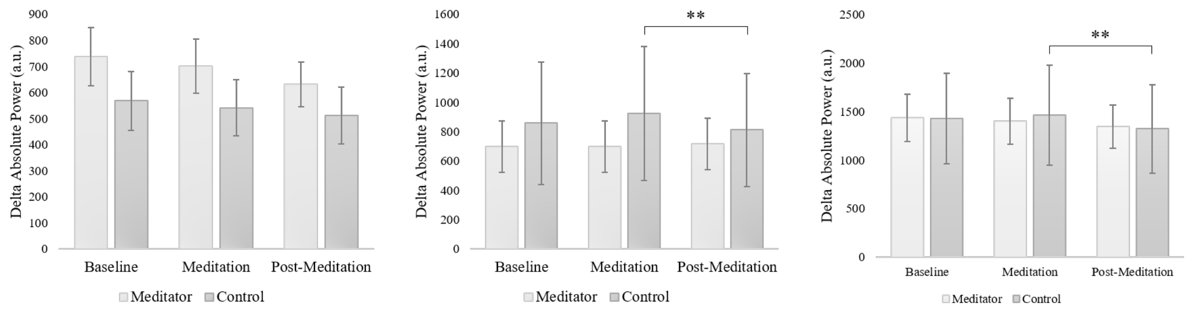


Figure 3.2: The corrected EEG signal without the OAs. The black line represents the raw EEG signal and the red line represents the EEG signal without the OAs, with epochs containing clipping events set to zero.

3.2 Group Analysis

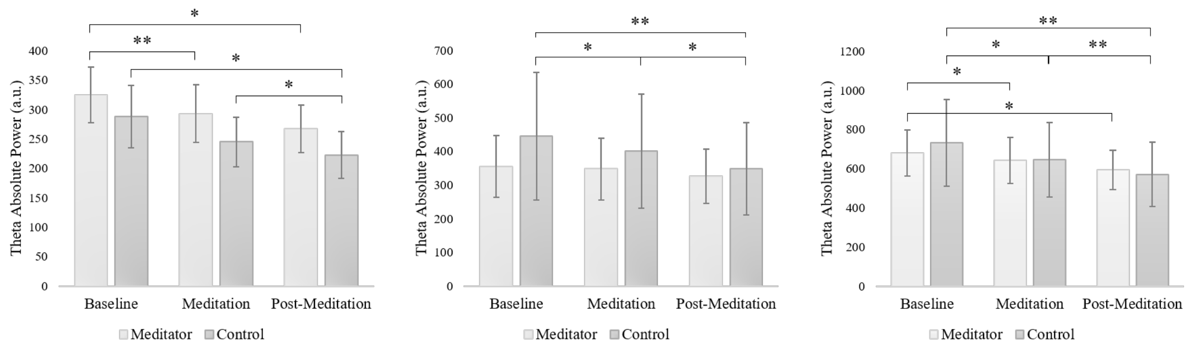
The following section presents the results of the EEG and PPG signals of the meditator and control groups during baseline, meditation and post-meditation periods. Only the parameters that revealed significant statistical differences are shown in this section. The statistically non-significant results can be found in Appendix B.1.



(a) (b) (c)

Figure 3.3: Absolute power of the delta band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

As shown in Figure 3.3, the absolute power of the delta band there were no significant differences between the meditator and control groups during each period for the left, right and both hemispheres. Additionally, the left hemisphere showed no significant difference between all three periods for the meditator (p = 0.273) and control (p = 0.717) groups (Figure 3.3a). However, the control group showed an almost significant increase between the baseline and meditation periods (p = 0.051) and a significant decrease between the meditation and post-meditation periods (p = 0.008) in the right hemisphere (Figure 3.3b). The control showed significant differences between all three periods (p=0.003) whereas the meditator group did not (p = 0.273). Finally, the combination of both hemispheres, i.e. left and right hemispheres, revealed a significant decrease between the meditation and post-meditation periods (p = 0.008) for the control group (Figure 3.3c). Finally, there were significant differences between all three periods for the control group (p = 0.004), however there were none for the meditator group (p = 0.273).



(a) (b) (c)

Figure 3.4: Absolute power of the theta band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

According to Figure 3.4, there were no significant differences in absolute theta power between the two groups during during each period for the left, right and both hemispheres. Nonetheless, the left hemisphere revealed a significant difference between all three periods for the meditator (p = 0.003) and control (p = 0.008) groups (Figure 3.4a). Additionally, the meditator group showed a significant decrease between the baseline and meditation periods (p = 0.007), and between the baseline and post-meditation periods (p = 0.028). The control group also revealed a significant decrease between the baseline and post-meditation periods (p = 0.015), and between the meditation and post-meditation periods (p = 0.038). The right hemisphere only showed a significant difference between all periods for the control group (p = 0.001), and not for the meditator group (p = 0.301) (Figure 3.4b). To add, the control group also demonstrated a significant decrease between the baseline and meditation periods (p = 0.011), meditation and post-meditation periods (p = 0.021), and baseline and post-meditation periods (p = 0.008). The combination of the left hemisphere with the right hemisphere revealed a significant difference between all periods for the meditator (p = 0.014) and control (p = 0.001) groups (Figure 3.4c). Additionally, there was a significant decrease between the baseline and meditation periods (p = 0.037) and baseline and post-meditation periods (p = 0.028) for the meditator group. To conclude, the control group revealed significant decreases between the baseline and meditation periods (p = 0.015), meditation and post-meditation periods (p = 0.008), and baseline and post-meditation periods (p = 0.008).

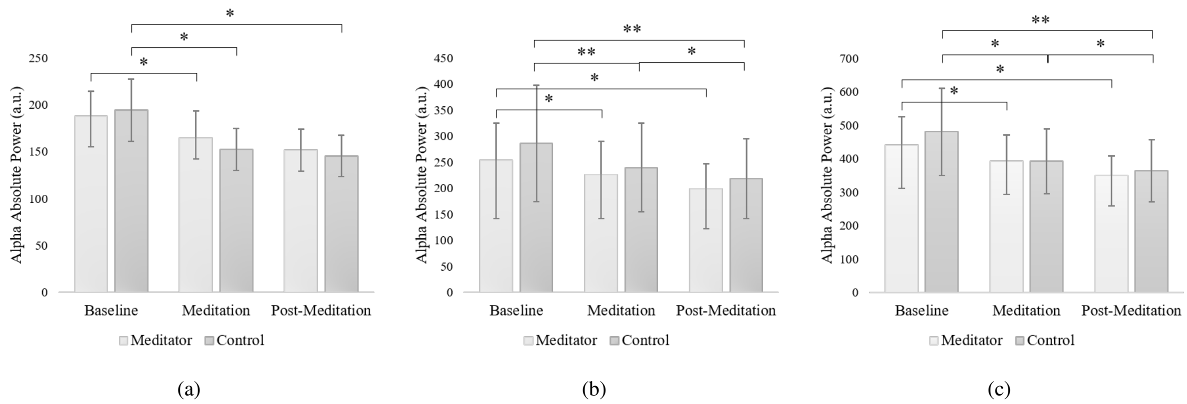
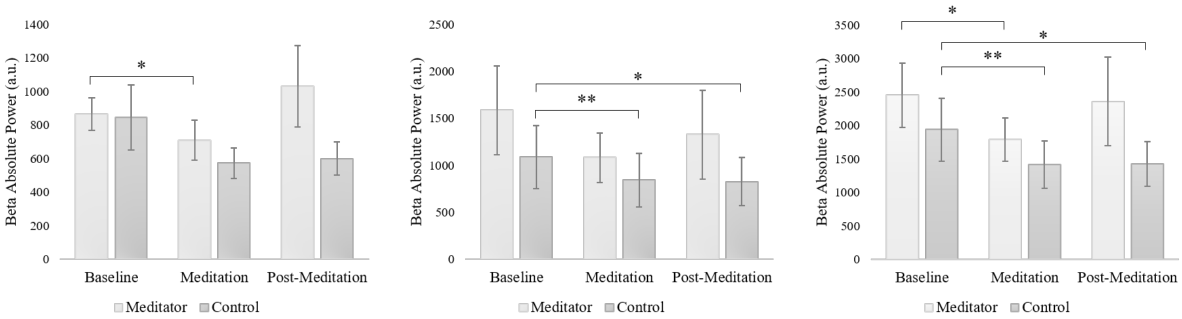


Figure 3.5: Absolute power of the alpha band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

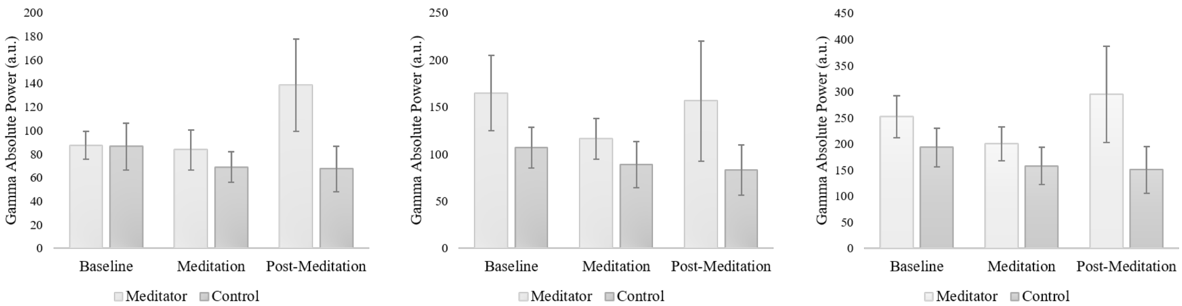
There were no significant differences in absolute alpha power between the meditator and control groups during during each period for the left, right and both hemispheres (Figure 3.5). The control group showed significant decreases in absolute power between the baseline and meditation periods (p = 0.028) and baseline and post-meditation periods (p = 0.015) for the left hemisphere (Figure 3.5a). The meditator group only showed a significant decrease between the baseline and meditation periods (p = 0.022). Additionally, the left hemisphere revealed a significant difference between all three periods for both the meditator (p = 0.007) and control (p = 0.013) groups. There was also a significant difference between all periods in the right hemisphere for both the meditator (p = 0.007) and control ($p < 0.001$) groups (Figure 3.5b). Additionally, the control group showed a significant decrease between the baseline and meditation periods (p = 0.008), meditation and post-meditation periods (p = 0.038) and baseline and post-meditation periods (p = 0.008). The meditator group only showed a significant decrease between the baseline and meditation periods (p = 0.047) and baseline and post-meditation periods (p = 0.013). There was a significant difference between all periods for the combination of both hemispheres, for the meditator (p = 0.014) and control (p = 0.001) groups (Figure 3.5c). In addition, there was a significant decrease between the baseline and meditation periods for the meditator (p = 0.022) and control (p = 0.021) groups. There was a significant decrease between the baseline and post-meditation periods as well for the meditator (p = 0.017) and control (p = 0.008) groups. Only the control group showed a significant decrease between the meditation and post-meditation periods (p = 0.011).



(a) (b) (c)

Figure 3.6: Absolute power of the beta band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with p $\leq$ 0.05, and ** indicates significant differences with p $\leq$ 0.01.

As shown in Figure 3.6, there were no significant differences between groups in the absolute power of the beta band for the left, right and both hemispheres. The left hemisphere showed no significant differences between all three periods for both the meditator (p = 0.150) and control (p = 0.236) groups (Figure 3.6a. However, the meditator group showed a significant decrease between the baseline and meditation periods (p = 0.047), and the control group showed an almost significant decrease (p = 0.051). The right hemisphere only showed a significant difference between all periods for the control group (p = 0.004), whereas the meditator group did not (p = 0.301) (Figure 3.6b). Additionally, the control group also revealed a significant decrease between the baseline and meditation periods (p = 0.008) and baseline and post-meditation periods (p = 0.015). The combination of both hemispheres showed a significant difference between all periods for the control group (p = 0.005), contrarily to the meditator group (p = 0.202) (Figure 3.6c). The meditator group revealed a significant difference between the baseline and meditation periods (p = 0.037), as well as the control group (p = 0.008). Additionally, the control group also showed a significant decrease between the baseline and post-meditation periods (p = 0.011).

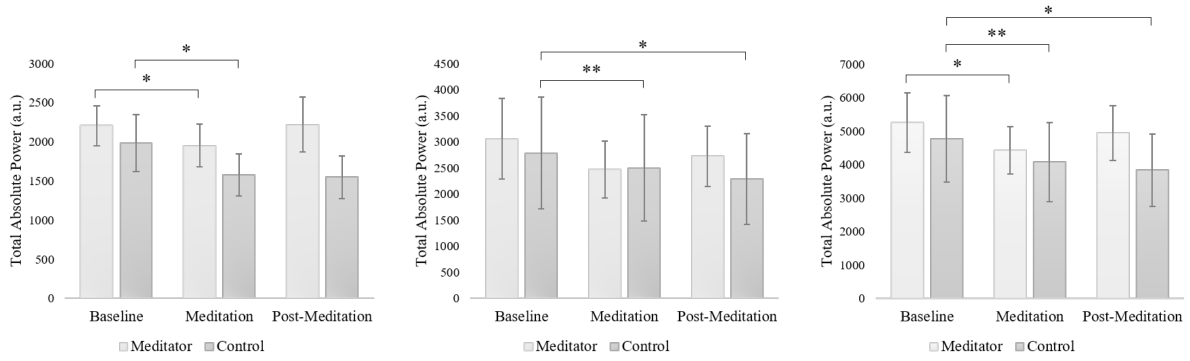


(a) (b) (c)

Figure 3.7: Absolute power of the gamma band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with p $\leq$ 0.05.

The absolute power of the gamma band showed no significant differences between the meditator and control groups during each period for the left, right and both hemispheres (Figure 3.7). The left hemisphere showed no significant differences between all periods for both the meditator (p = 0.741) and control (p = 0.264) groups (Figure 3.7a). The right hemisphere revealed a significant difference between all three periods for the control group (p = 0.032), but not for the meditator groups (p = 0.150)

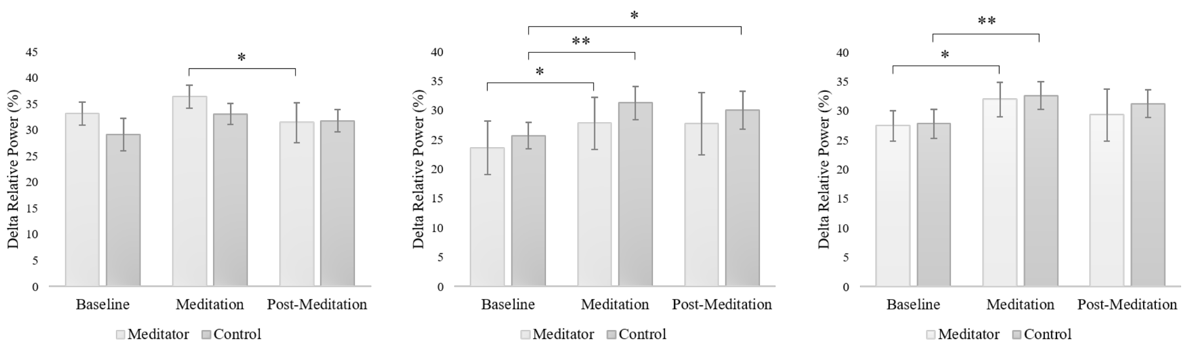
(Figure 3.7b). In addition, the control group also showed an almost significant decrease in gamma power between the baseline and post-meditation periods (p = 0.051). Finally, the combination of both hemispheres revealed no significant differences between all three periods for the both the meditator (p = 0.407) and control (p = 0.062) groups (Figure 3.7c).



(a) (b) (c)

Figure 3.8: Absolute power of all the bands for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

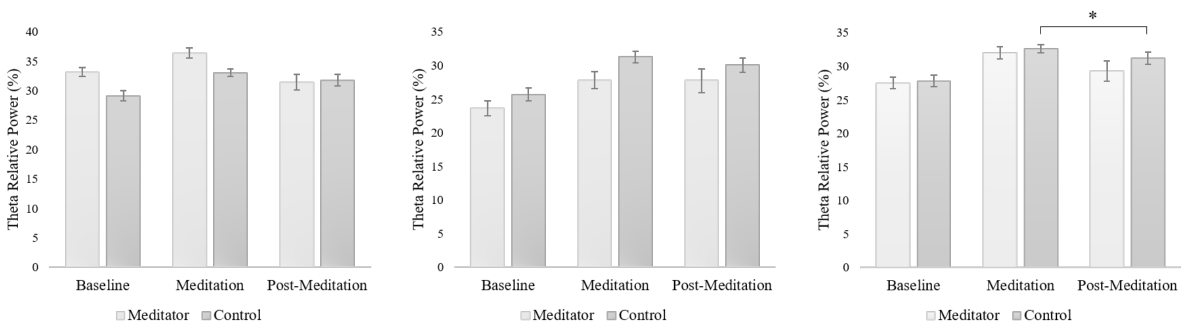
As shown in Figure 3.8, there were no significant differences between the meditator and control groups during each period for the left, right and both hemispheres. The left hemisphere showed no significant differences between all three periods for both the meditator (p = 0.273) and control (p = 0.097) groups (Figure 3.8a). The meditator group showed a significant decrease between the baseline and meditation periods (p = 0.028). The control group revealed significant decreases between the baseline and meditation periods (p = 0.038) and an almost significant decrease between the baseline and post-meditation periods (p = 0.051). There was a significant difference between all periods for the control group (p = 0.003) in the right hemisphere (Figure 3.8b). The meditator group showed no significant differences (p = 0.273). Additionally, the control group showed a significant decrease between the baseline and meditation periods (p = 0.008) and baseline and post-meditation periods (p = 0.011). To conclude, the combination of both hemispheres only showed a significant difference between all three periods for the control group (p = 0.003), whereas the meditator group did not show (p = 0.202) (Figure 3.8c). However, the meditator did show a significant decrease between the baseline and meditation periods (p = 0.037). The control group also revealed significant decreases between the baseline and meditation periods (p = 0.008) and meditation periods, an almost significant decrease between the baseline and post-meditation periods (p = 0.051) and a significant decrease between the baseline and post-meditation periods (p = 0.011).



(a) (b) (c)

Figure 3.9: Relative power of the delta band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with p $\leq$ 0.05, and ** indicates significant differences with p $\leq$ 0.01.

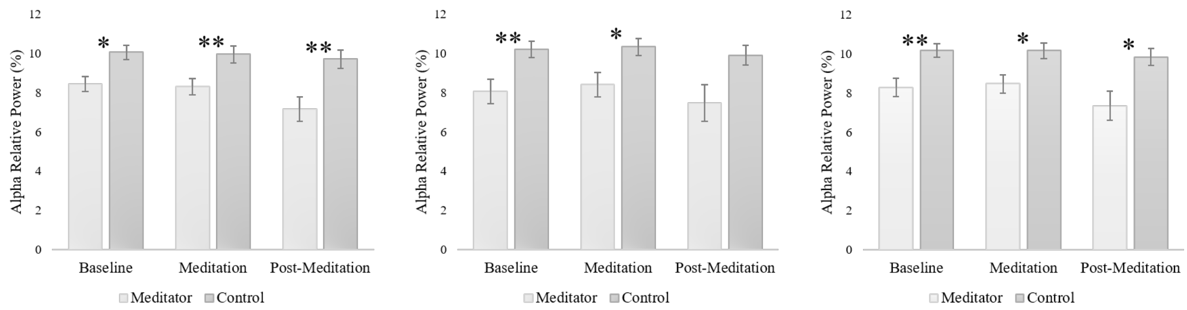
The relative delta power shown in Figure 3.9 revealed no significant differences between the control and meditator groups during each period for the left, right and both hemispheres. The left hemisphere showed a significant decrease in power between the meditation and post-meditation periods for the meditator group (p = 0.022) (Figure 3.9a). Additionally, there were no significant differences between all three periods for the meditator (p = 0.082) and control (p = 0.459) groups. The right hemisphere showed a significant difference between all periods for the control group (p = 0.016), whereas the meditator group did not (p = 0.150) (Figure 3.9b). The control group also revealed a significant increase between the baseline and meditation periods (p = 0.008) and a decrease between the baseline and post-meditation periods (p = 0.038). The meditator group only revealed a significant increase between the baseline and meditation periods (p = 0.037). The combination of both hemispheres showed a significant difference between all periods for the control group (p = 0.016) (Figure 3.9c). The same was not valid for the meditator group (p = 0.067). There was a significant increase between the baseline and meditation periods for the meditator (p = 0.017) and control (p = 0.008) groups.



(a) (b) (c)

Figure 3.10: Relative power of the theta band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with p $\leq$ 0.05.

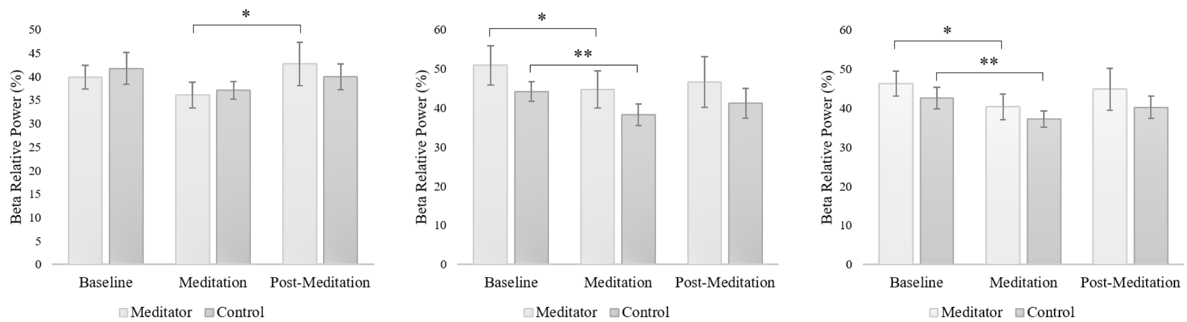
As shown in Figure 3.10, there were no significant differences between the meditator and control groups during each period for the left, right and both hemispheres. The left hemisphere showed no significant differences between all three periods for the meditator (p = 0.497) and control (p = 0.459) groups (Figure 3.10a). Also, there were no significant differences between all periods for the meditator (p = 0.273) and control (p = 0.368) groups the right hemisphere (Figure 3.10b). Additionally, the combination of both hemispheres showed no significant differences between all periods for the meditator (p = 0.150) and control (p = 0.121) groups (Figure 3.10c). However, the control revealed a significant decrease between the meditation and post-meditation periods (p = 0.038).



(a) (b) (c)

Figure 3.11: Relative power of the alpha band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

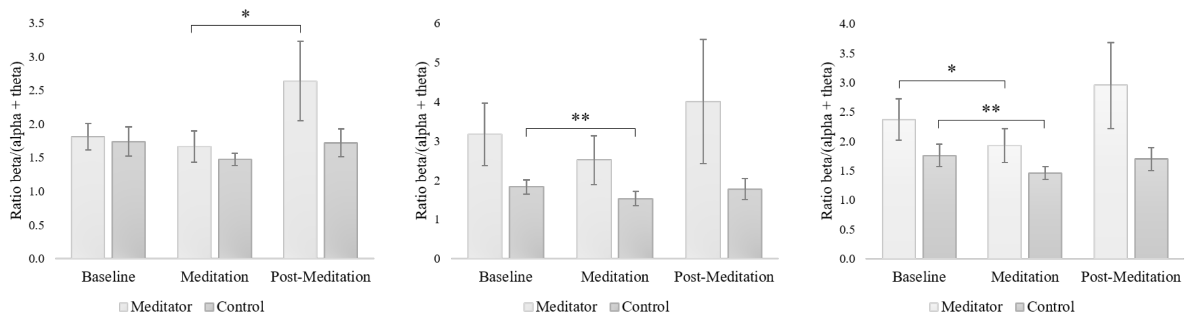
As shown in Figure 3.11, the relative power of the alpha band showed significant differences between the meditator and control groups during each period for the left, right and both hemisphere. For the left hemisphere, the control group showed significantly higher values when compared to the meditator group during the baseline (p = 0.013), meditation (p = 0.010) and post-meditation (p = 0.003) periods (Figure 3.11a). However, there were no significant differences between all three periods for the control (p = 0.459) and meditator (p = 0.497) groups. The control group also showed significantly higher values in the right hemisphere for the relative alpha band compared to the meditator group during the baseline (p = 0.010) and meditation (p = 0.013) periods, and an almost significant difference during the post-meditation period (p = 0.053) (Figure 3.11b). However there were no significant differences between all three periods for the meditator (p = 0.301) and control (p = 0.459) groups. Finally, the combination of both hemispheres revealed significantly higher values for the control group compared to the meditation group during the baseline (p = 0.004), meditation (p = 0.028) and post-meditation (p = 0.013) periods (Figure 3.11c). There were no significant differences between all periods for the control (p = 0.895) and meditator (p = 0.301) groups.



(a) (b) (c)

Figure 3.12: Relative power of the beta band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

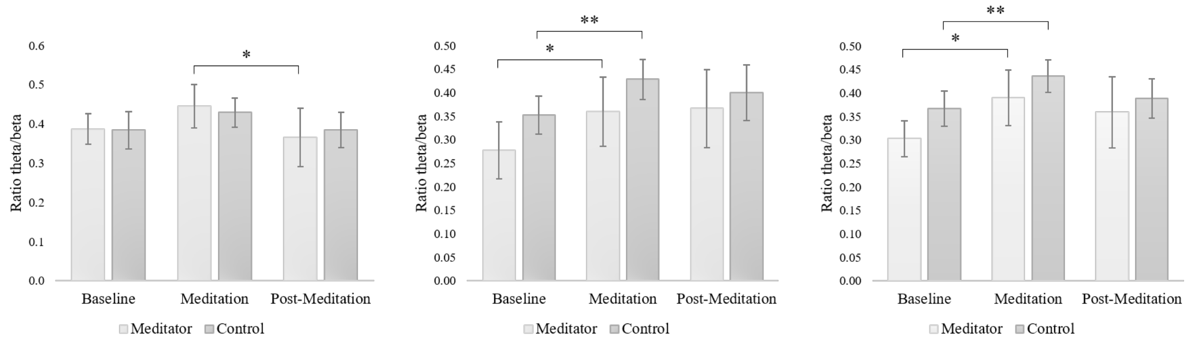
There were no significant differences between in the relative beta power the two groups during each period for the left, right and both hemispheres (Figure 3.12). The left hemisphere showed a significant increase between the meditation and post-meditation periods for meditator group (p = 0.022) (Figure 3.12a). There were no significant differences between all three periods for the meditator (p = 0.061) and control (p = 0.236) groups. The right hemisphere revealed a significant difference between all periods for the control group (p = 0.018), contrarily to the meditator group which did not (p = 0.067) (Figure 3.12b). Additionally, there was a significant decrease between the baseline and meditation periods for the meditator (p = 0.047) and control (p = 0.008) groups. Finally, there was significant differences between all periods for the combination of both hemispheres for the meditator (p = 0.045) and control (p = 0.008) groups (Figure 3.12c). There was a significant decrease between the baseline and meditation periods for both the meditator (p = 0.017) and control (p = 0.008) groups.



(a) (b) (c)

Figure 3.13: Ratio beta/(alpha + theta) for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with p $\leq$ 0.05, and ** indicates significant differences with p $\leq$ 0.01.

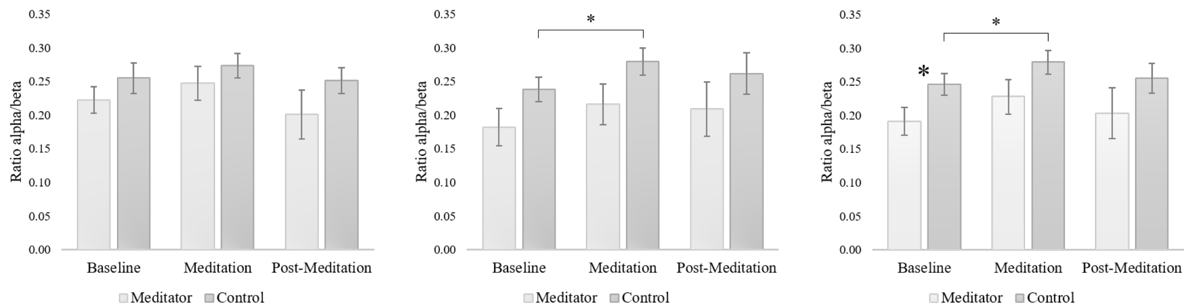
As Figure 3.13 shows, there were no significant differences in the beta/(alpha + theta) ratio between the meditator and control groups during each period for the left, right and both hemispheres. However, the meditator group showed a significant difference between all three periods for the left hemisphere (p = 0.045), whereas the control group did not (p = 0.121) (Figure 3.13a). Additionally, the meditator group also revealed a significant increase between the meditation and post-meditation periods (p = 0.017). The right hemisphere showed significant differences between all periods for the control group (p = 0.008), contrarily to the meditator group which did not (p = 0.150) (Figure 3.13b). In addition, the control group showed a significant decrease between the baseline and meditation periods (p = 0.008). Finally, the combination of both hemispheres only showed significant differences between the three periods for the control group (p = 0.018), and the meditator group did not (p = 0.150) (Figure 3.13c). There was also a significant decrease between the baseline and meditation periods for the meditator (p = 0.028) and control (p = 0.008) groups.



(a) (b) (c)

Figure 3.14: Ratio theta/beta for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

As shown in Figure 3.14, there were no significant differences in the theta/beta ratio between the meditator and control groups during each period for the left, right and both hemispheres. The left hemisphere showed a significant decrease between the meditation and post-meditation periods for the meditator (p = 0.047) group, and the control group showed an almost significant difference (p = 0.051) (Figure 3.14a).Neither the meditator (p = 0.122) and control (p = 0.121) groups showed significant differences between all periods. The right hemisphere showed significant differences between all periods for the control group (p = 0.013), and the meditator group did not (p = 0.061) (Figure 3.14b). Also, the control group revealed and significant increase between the baseline and meditation periods (p = 0.008), as well as the meditator group (p = 0.017). The combination of both hemispheres showed significant differences between the three periods for the control group (p = 0.032), whilst the meditator group did not (p = 0.122) (Figure 3.14c). There was also a significant increase between the baseline and meditation periods for the meditator (p = 0.028) and control (p = 0.008) groups.



(a) (b) (c)

Figure 3.15: Ratio alpha/beta for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$.

As shown in Figure 3.15 here were no significant differences between groups during each periods for the left and right hemisphere, however the combination of both hemispheres showed a significantly higher alpha/beta for the control group compared to the meditator group during the baseline period (p = 0.043). The left hemisphere revealed no significant differences between all periods for both the meditator (p = 0.061) and control (p = 0.264) groups (Figure 3.15a). There was a significant increase for the control group between the baseline and meditation periods (p = 0.021) (Figure 3.15b). In addition, there were no significant differences between all periods for the meditator (p = 0.202) and control (p = 0.097) groups. Finally, the combination of both hemispheres showed a significant increase for the control group between the baseline and meditation periods (p = 0.021) (Figure 3.15c). There were no significant differences between all periods for the meditator (p = 0.150) and control (p = 0.097) groups.

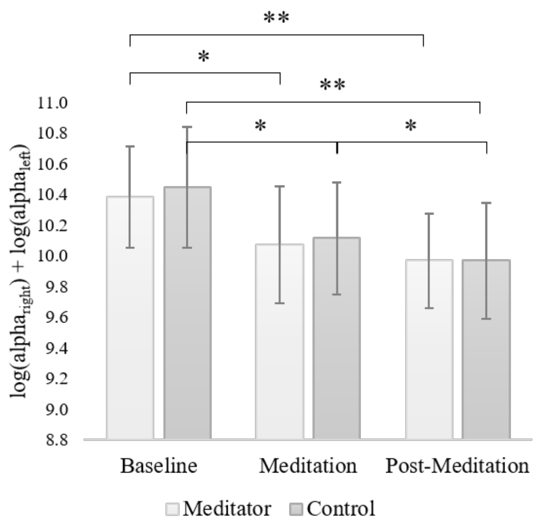


Figure 3.16: Arousal for the meditator and control groups during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

As shown in Figure 3.16, there were no significant differences in arousal between groups during each periods. However, the meditator group showed a significant decrease between the baseline and meditation periods (p = 0.017) and between the baseline and post-meditation periods (p = 0.009). Also, the control group showed a significant decrease between the baseline and meditation periods (p = 0.015), meditation and post-meditation periods (p = 0.021), and baseline and post-meditation (p = 0.008). Finally, there were significant differences between all periods for the meditator (p = 0.014) and control (p = 0.002) groups.

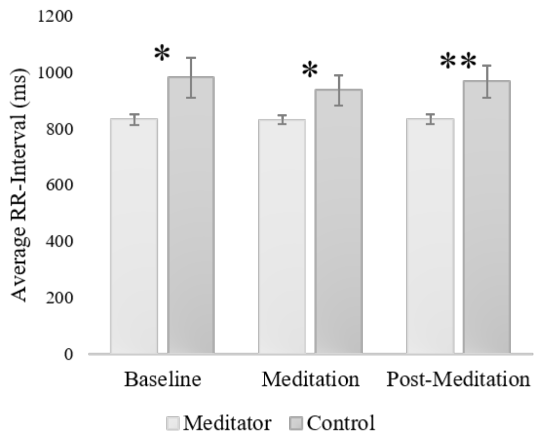


Figure 3.17: Average RR-Interval for meditator and control groups during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

The average RR-interval was significantly lower for the meditator group in comparison to the control group during the baseline (p = 0.035), meditation (p = 0.017) and post-meditation (p = 0.004) periods (Figure 3.17). Additionally, the control group also showed an almost significant increase between the meditation and post-meditation periods (p = 0.051). Finally, there were no significant differences between all three periods for the meditator (p = 0.905) and control (p = 0.121) groups.

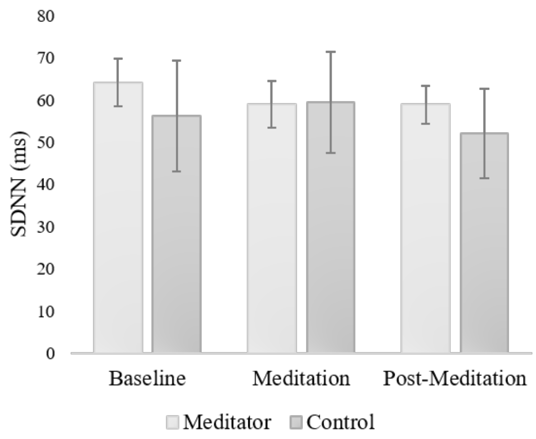


Figure 3.18: SDNN for meditator and control groups during the baseline, meditation and post-meditation periods. The * indicates significant differences with p ≤ 0.05.

As shown in Figure Figure 3.18, there were no significant differences between the meditator and control groups during each period. However, the control group showed an almost significant decrease between the meditation and post-meditation periods (p = 0.051). To add, there were no significant differences between all periods for the meditator (p = 0.273) and control (p = 0.097) groups.

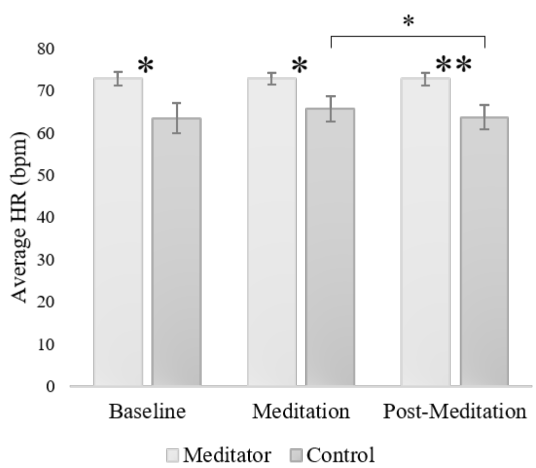


Figure 3.19: Average HR for meditator and control groups the during baseline, meditation and post-meditation periods. The * indicates significant differences with p ≤ 0.05, and ** indicates significant differences with p ≤ 0.01.

The average HR was significantly higher for the meditator group in comparison to the control group during the baseline (p = 0.035), meditation (p = 0.017) and post-meditation (p = 0.004) periods (Figure 3.19). Additionally, the control group also showed a significant decrease between meditation and post-meditation (p = 0.038) periods. There were no significant differences between all three periods for the meditator (p = 0.905) and control (p = 0.121) groups.

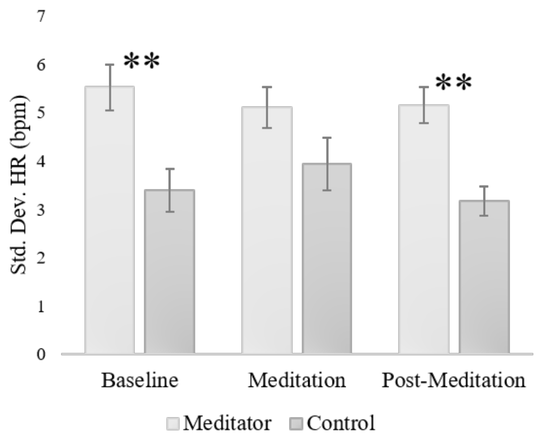


Figure 3.20: Standard deviation of the HR for meditator and control groups during the baseline, meditation and post-meditation periods. The * indicates significant differences with p $\leq$ 0.05, and ** indicates significant differences with p $\leq$ 0.01.

The standard deviation of the HR was significantly higher for the meditator groups in comparison to the control group during the baseline (p = 0.003) and post-meditation (p = 0.002) periods (Figure 3.20). However, the control group showed an almost significant decrease between the meditation and post-meditation periods (p = 0.051). Finally, there were no significant differences between all three periods for the meditator (p = 0.407) and control (p = 0.062) groups.

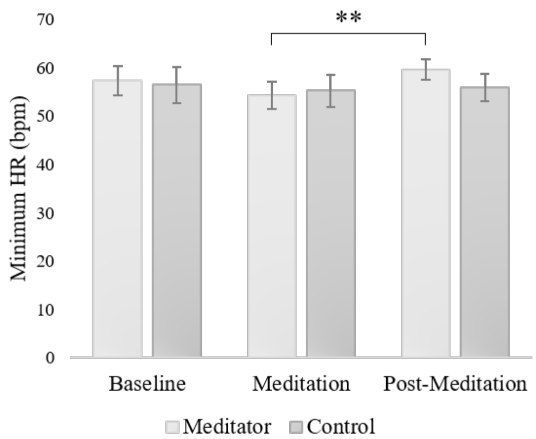


Figure 3.21: Minimum HR for meditator and control groups during the baseline, meditation and post-meditation periods. The * indicates significant differences with p $\leq$ 0.05, and ** indicates significant differences with p $\leq$ 0.01.

As the Figure 3.21 shows, the minimum HR revealed no significant differences between the meditator and control groups during each period. Nevertheless, the meditator group showed a significant increase between the meditation and post-meditation periods (p = 0.008). Additionally, the meditator group revealed a significant difference between all three periods (p = 0.003), whereas the control group did not (p = 0.641).

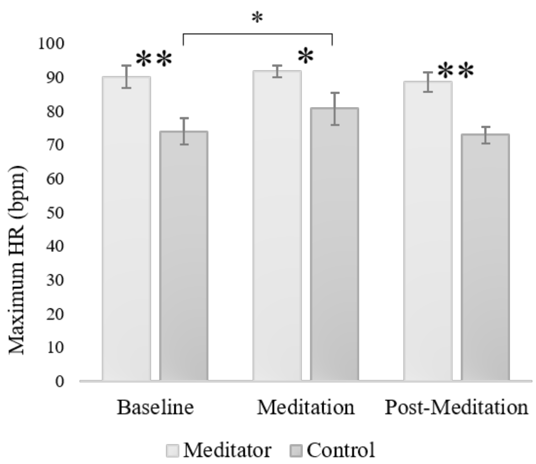


Figure 3.22: Maximum HR for meditator and control groups during the baseline, meditation and post-meditation periods. The * indicates significant differences with p $\leq$ 0.05, and ** indicates significant differences with p $\leq$ 0.01.

The maximum HR was significantly higher for the meditator group compared to the control group during the baseline (p = 0.006), meditation (p = 0.043) and post-meditation (p = 0.001) periods (3.22). However, only the control group showed a significant increase between the baseline and meditation periods (p = 0.036). Additionally, all three periods revealed no significant differences for the meditator (p = 0.562) and control (p = 0.293) groups.

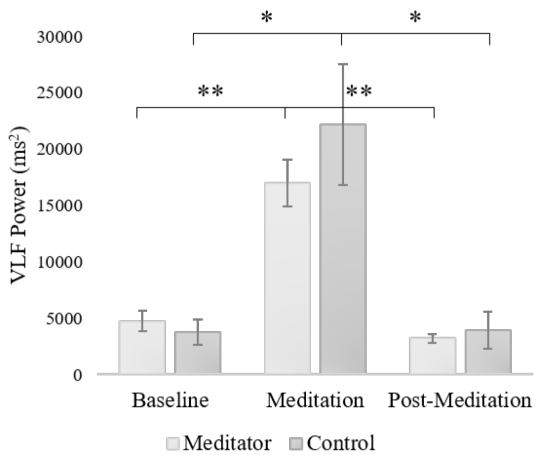


Figure 3.23: VLF power for meditator and control groups during the baseline, meditation and post-meditation periods. The ** indicates significant differences with p $\leq$ 0.01.

As shown in Figure 3.23, there were no significant differences in the VLF power between the meditator and control groups during each period. However, there was a significant increase between the baseline and meditation periods for the meditator (p = 0.005) and control (p = 0.011) groups. Also, the meditation and post-meditation periods showed a significant decrease for the meditator (p = 0.005) and control (p = 0.011) groups. Finally, there was a significant difference between all three periods for both the meditator ($p < 0.001$) and control (p = 0.013) groups.

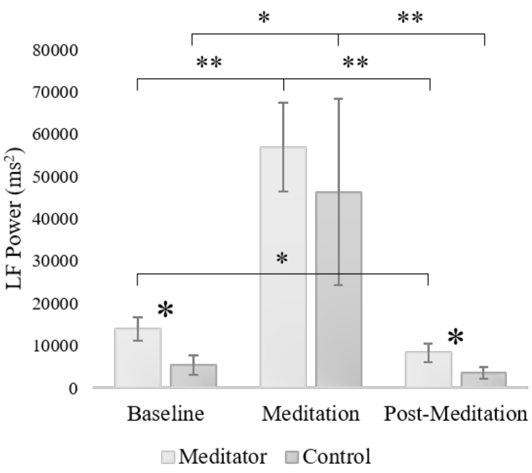


Figure 3.24: LF power for meditator and control groups during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

The LF power was significantly higher for the meditator group in comparison to the control group during the baseline (p = 0.017) and post-meditation (p = 0.035) periods (Figure 3.24). Additionally, there was a significant increase between the baseline and meditation periods for the meditator (p = 0.005) and control (p = 0.011) groups. The meditation and post-meditation periods showed a significant decrease for the meditator (p = 0.005) and control (p = 0.008) groups. Also, there was a significant decrease between the baseline and meditation periods for the meditator group (p = 0.022), and control group showed an almost significant decrease (p = 0.051). To conclude, there was a significant difference between all periods for both the meditator ($p < 0.001$) and control (p = 0.002) groups.

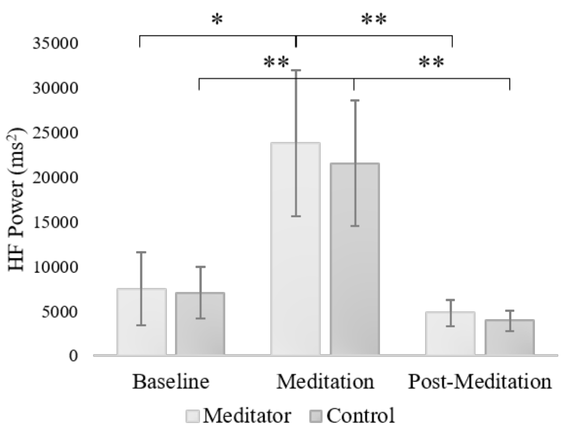


Figure 3.25: HF power for meditator and control groups during baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

The HF power showed no significant differences between both groups during each period (Figure 3.25). However, there was a significant increase between the baseline and meditation periods for the meditator (p = 0.022) and control (p = 0.008) groups. Additionally, the meditation and post-meditation periods showed a significant decrease for the meditator (p = 0.005) and control (p = 0.008) groups. Finally, there was a significant difference between all periods for the meditator (p = 0.002) and control (p = 0.001) groups.

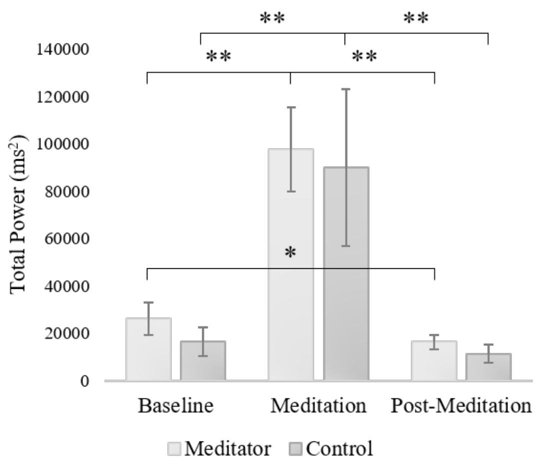


Figure 3.26: Total power for meditator and control groups during baseline, meditation and post-meditation periods. The ** indicates significant differences with p $\leq$ 0.01.

As shown in Figure 3.26, the total power of the HRV showed no significant differences between both groups during each period. The baseline and meditation periods showed a significant increase for the meditator (p = 0.005) and control (p = 0.008) groups. Additionally, there was a significant decrease between meditation and post-meditation periods for the meditator (p = 0.005) and control (p = 0.008) groups. Only the meditator group showed a significant decrease between the baseline and meditation periods (p = 0.037). Finally, there was a significant difference between all three periods for both the meditator (p $<$ 0.001) and control (p = 0.001) groups.

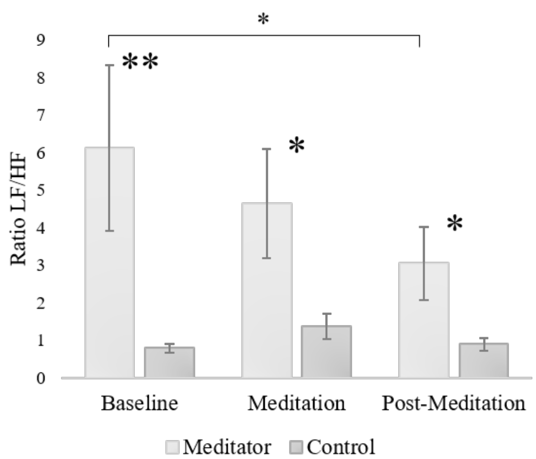


Figure 3.27: Ratio LF/HF for meditator and control groups during baseline, meditation and post-meditation periods. The * indicates significant differences with p $\leq$ 0.05, and ** indicates significant differences with p $\leq$ 0.01.

The LF/HF ratio was significantly higher for the meditator group compared to the control group the baseline (p = 0.006), meditation (p = 0.022) and post-meditation (p = 0.022) periods (Figure 3.27). Additionally, the meditator group revealed a significant decrease between the baseline and post-meditation (p = 0.047) periods. Only the meditator group exhibited significant differences between all three periods (p = 0.045), whereas the control group did not (p = 0.459).

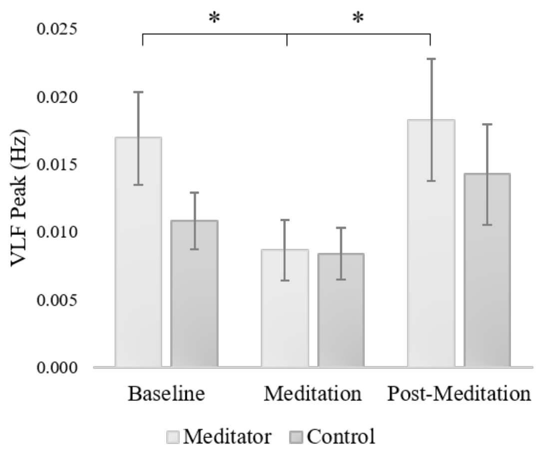


Figure 3.28: VLF peak for meditator and control groups during baseline, meditation and post-meditation periods. The * indicates significant differences with p $\leq$ 0.05.

As Figure 3.28 shows, the VLF peak showed no significant differences between the meditator and control groups during each period. The meditator group revealed a significant decrease between the baseline and meditation periods (p = 0.017) and an increase between the meditation and post-meditation periods (p = 0.047). Additionally, the meditator group showed significant differences between all periods (p = 0.025), and the control group did not (p = 0.459).

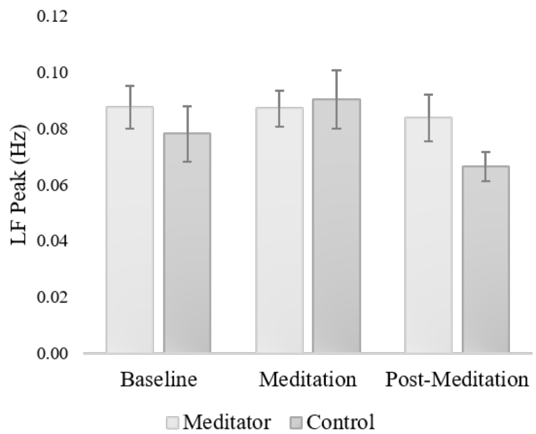
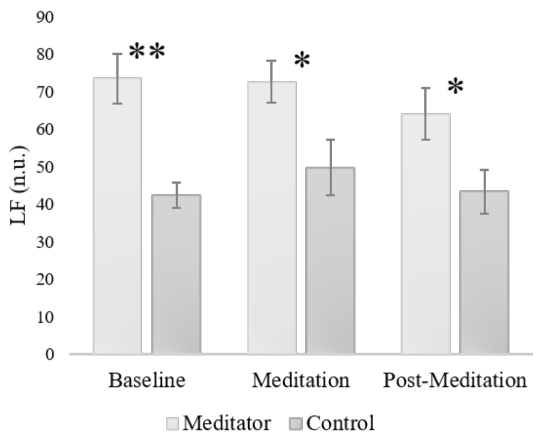
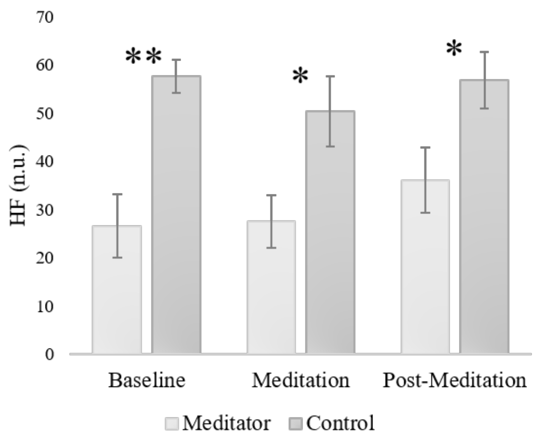


Figure 3.29: LF peak for meditator and control groups during baseline, meditation and post-meditation periods. The * indicates significant differences with p $\leq$ 0.05.

As the Figure Figure 3.29 shows, there were no significant differences in the LF peak between the meditator and control groups during each period. However, the control revealed an almost significant decrease between the meditation and post-meditation periods (p = 0.051). There were no significant differences between all three periods for the control (p = 0.459) and meditator (p = 0.497) groups.



(a)



(b)

Figure 3.30: (a) LF (n.u.) and (b) HF (n.u.) for the meditator and control groups during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

The LF power (n.u.) showed significant differences between both groups during the baseline (p = 0.006), meditation (p = 0.022) and post-meditation (p = 0.022) (Figure 3.30a). There were no significant differences between pairs of periods for both groups, however the meditator group showed significant differences between all three periods (p = 0.045) whereas the control group did not (p = 0.459). Similarly to the LF power (n.u.), the HF (n.u.) also showed significant differences between both groups during the baseline (p = 0.006), meditation (p = 0.022) and post-meditation (p = 0.022) (Figure 3.30b). There were no significant differences between pairs of periods for both groups, however the meditator group showed significant differences between all three periods (p = 0.045) whereas the control group did not (p = 0.459).

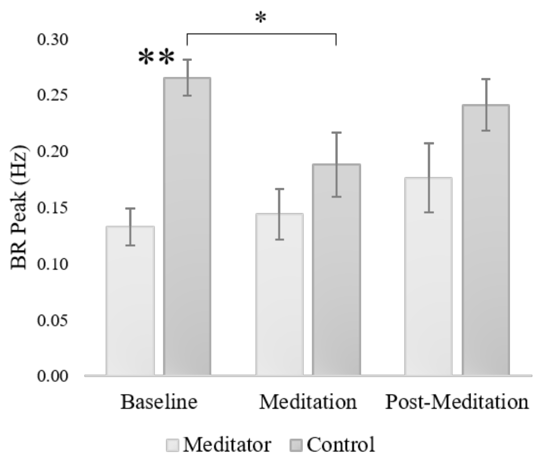


Figure 3.31: BR peak, i.e. average BR, for meditator and control groups during baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$, and ** indicates significant differences with $p \leq 0.01$.

The average breathing rate was significantly lower for the meditator group in comparison to the control group during the baseline (p = 0.001) period, and an almost significant lower value during the post-meditation period (p = 0.053) (Figure 3.31). Additionally, the control group showed a significant decrease between the baseline and meditation (p = 0.038) periods. There were no significant differences between all three periods for the meditator (p = 0.497) and control (p = 0.368) groups.

The Figures 3.32, 3.33, 3.34, 3.35 and 3.36 show the summarized findings between groups in each period, as well as the differences for each group between paired-periods.

EEG (Left Hemisphere)		Groups			Periods		
		B	**M**	**PM**	**B/M**	**M/PM**	**B/PM**
Absolute Power	**Delta**	–	–	–	–	–	–
	Theta	–	–	–	↓ **Me***	↓ C	↓ Me ↓ C
	Alpha	–	–	–	↓ Me ↓ C	–	↓ C
	Beta	–	–	–	↓ Me	–	–
	Gamma	–	–	–	–	–	–
	Total	–	–	–	↓ Me ↓ C	–	–
Relative Power	**Delta**	–	–	–	–	↓ Me	–
	Theta	–	–	–	–	–	–
	Alpha	↓ Me	↓ **Me***	↓ **Me***	–	–	–
	Beta	–	–	–	–	↑ Me	–
	Gamma	–	–	–	–	–	–
Ratio	**Beta/(Alpha + Theta)**	–	–	–	–	↑ Me	–
	Theta/Beta	–	–	–	–	↓ Me	–
	Alpha/Beta	–	–	–	–	–	–

Figure 3.32: The significant EEG findings in the left hemisphere between the meditator and control groups, during each period, as well as the differences between each pair of periods for both groups. The * stands for $p \leq 0.01$. B = Baseline, M = Meditation, PM = Post-Meditation, C = Control, Me = Meditator, ↓ = lower/decrease in value, ↑ = higher/increase in value.

EEG (Right Hemisphere)		Groups			Periods		
		B	**M**	**PM**	**B/M**	**M/PM**	**B/PM**
Absolute Power	**Delta**	–	–	–	–	↓ **C***	–
	Theta	–	–	–	↓ C	↓ C	↓ **C***
	Alpha	–	–	–	↓ Me ↓ **C***	↓ C	↓ Me ↓ **C***
	Beta	–	–	–	↓ **C***	–	↓ C
	Gamma	–	–	–	–	–	–
	Total	–	–	–	↓ **C***	–	↓ C
Relative Power	**Delta**	–	–	–	↑ Me ↑ **C***	–	↑ C
	Theta	–	–	–	–	–	–
	Alpha	↓ **Me***	↓ Me	–	–	–	–
	Beta	–	–	–	↓ Me ↓ **C***	–	–
	Gamma	–	–	–	–	–	–
Ratio	**Beta/(Alpha + Theta)**	–	–	–	↓ **C***	–	–
	Theta/Beta	–	–	–	↑ Me ↑ **C***	–	–
	Alpha/Beta	–	–	–	↑ C	–	–

Figure 3.33: The significant EEG findings in the right hemisphere between the meditator and control groups, during each period, as well as the differences between each pair of periods for both groups. The * stands for $p \leq 0.01$. B = Baseline, M = Meditation, PM = Post-Meditation, C = Control, Me = Meditator, ↓ = lower/decrease in value, ↑ = higher/increase in value.

EEG (Both Hemispheres)		Groups			Periods		
		B	M	PM	B/M	M/PM	B/PM
Absolute Power	Delta	–	–	–	–	↓ **C***	–
	Theta	–	–	–	↓ Me ↓ C	↓ **C***	↓ Me ↓ **C***
	Alpha	–	–	–	↓ Me ↓ C	↓ C	↓ Me ↓ **C***
	Beta	–	–	–	↓ Me ↓ **C***	–	↓ C
	Gamma	–	–	–	–	–	–
	Total	–	–	–	↓ Me ↓ **C***	–	↓ C
Relative Power	Delta	–	–	–	↑ Me ↑ **C***	–	–
	Theta	–	–	–	–	↓ C	–
	Alpha	↓ **Me***	↓ Me	↓ Me	–	–	–
	Beta	–	–	–	↓ Me ↓ **C***	–	–
	Gamma	–	–	–	–	–	–
Ratio	Beta/(Alpha + Theta)	–	–	–	↓ Me ↓ **C***	–	–
	Theta/Beta	–	–	–	↑ Me ↑ **C***	–	–
	Alpha/Beta	↓ Me	–	–	↑ C	–	–

Figure 3.34: The significant EEG findings in both hemispheres between the meditator and control groups, during each period, as well as the differences between each pair of periods for both groups. The * stands for $p \leq 0.01$. B = Baseline, M = Meditation, PM = Post-Meditation, C = Control, Me = Meditator, ↓ = lower/decrease in value, ↑ = higher/increase in value.

EEG	Groups			Periods		
	B	M	PM	B/M	M/PM	B/PM
Valence	–	–	–	–	–	–
Arousal	–	–	–	↓ Me ↓ C	↓ C	↓ Me* ↓ C*

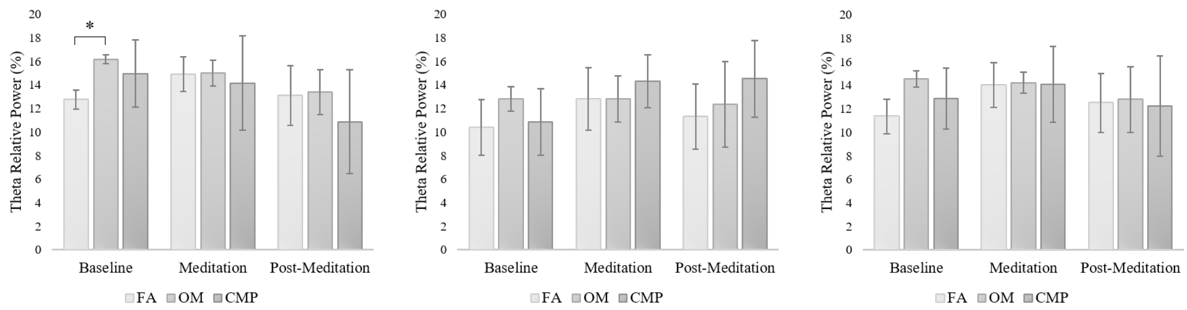
Figure 3.35: The significant EEG findings for the arousal and valence metrics between the meditator and control groups, during each period, as well as the differences between each pair of periods for both groups. The * stands for $p \leq 0.01$. B = Baseline, M = Meditation, PM = Post-Meditation, C = Control, Me = Meditator, ↓ = lower/decrease in value, ↑ = higher/increase in value.

PPG		Groups			Periods		
		B	M	PM	B/M	M/PM	B/PM
Average RR-interval		↓ Me	↓ Me	↓ **Me***	–	–	–
SDNN		–	–	–	–	–	–
Average HR		↑ Me	↑ Me	↑ **Me***	–	↓ C	–
Std. Dev. HR		↑ **Me***	–	↑ **Me***	–	–	–
Minimum HR		–	–	–	–	↑ **Me***	–
Maximum HR		↑ **Me***	↑ Me	↑ **Me***	↑ C	–	–
RMSSD		–	–	–	–	–	–
pNN50		–	–	–	–	–	–
Power	VLF	–	–	–	↑ **Me*** ↑ C	↓ **Me*** ↓ C	–
	LF	↑ Me	–	↑ Me	↑ **Me*** ↑ C	↓ **Me*** ↓ **C***	↓ Me ↓ C
	HF	–	–	–	↑ Me ↑ **C***	↓ **Me*** ↓ **C***	–
	Total	–	–	–	↑ **Me*** ↑ **C***	↓ **Me*** ↓ **C***	–
Ratio LF/HF		↑ **Me***	↑ Me	↑ Me	–	–	↓ Me
Power (n.u.)	LF	↑ **Me***	↑ Me	↑ Me	–	–	–
	HF	↓ **Me***	↓ Me	↓ Me	–	–	–
Peak	VLF	–	–	–	↓ Me	↑ Me	–
	LF	–	–	–	–	–	–
	HF	–	–	–	–	–	–
Average BR		↓ **Me***	–	–	↓ C	–	–

Figure 3.36: The significant PPG findings between the meditator and control groups, during each period, as well as the differences between each pair of periods for both groups. The * stands for $p \leq 0.01$. B = Baseline, M = Meditation, PM = Post-Meditation, C = Control, Me = Meditator, ↓ = lower/decrease in value, ↑ = higher/increase in value.

3.3 Practice Analysis

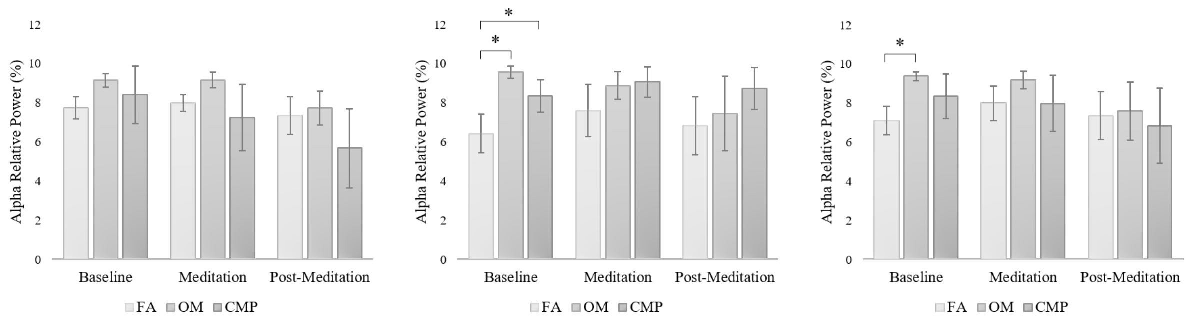
The following section presents the results of the EEG and PPG signals of the three practices in each period. Only the parameters that revealed significant statistical differences were shown in this section. The other results may be found in Appendix B.2.



(a) (b) (c)

Figure 3.37: Relative power of theta band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$.

As shown in Figure 3.37, the relative power was significantly lower for the FA meditation practice in comparison to the OM meditation practice during the baseline period (p = 0.029) in the right hemisphere.



(a) (b) (c)

Figure 3.38: Relative power of alpha band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres. The * indicates significant differences with $p \leq 0.05$.

The FA meditation practice showed a significantly lower relative alpha power in comparison to the OM meditation practice during the baseline period (p = 0.029) (Figure 3.38b). Also, there were significant differences between all three meditation practices during the baseline period (p = 0.037). The combination of both hemispheres showed a significantly higher value for the OM meditation practice in comparison to the FA meditation practice during the baseline period (p = 0.029) (Figure 3.38c).

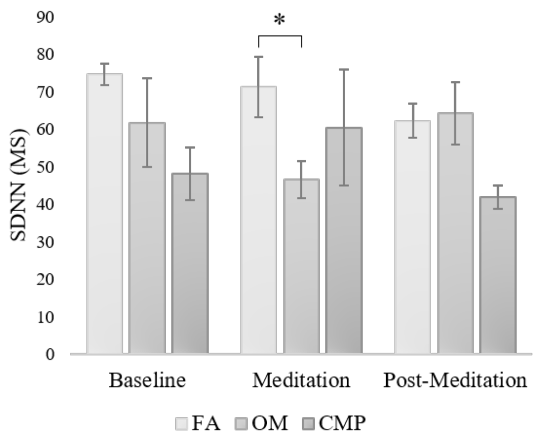


Figure 3.39: SDNN for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods. The * indicates significant differences with p $\leq$ 0.05.

As shown in Figure 3.39, the SDNN was significantly higher for the FA meditation practice in comparison to the OM meditation practice (p = 0.029). There were no other significant differences between the different meditation practices for each period.

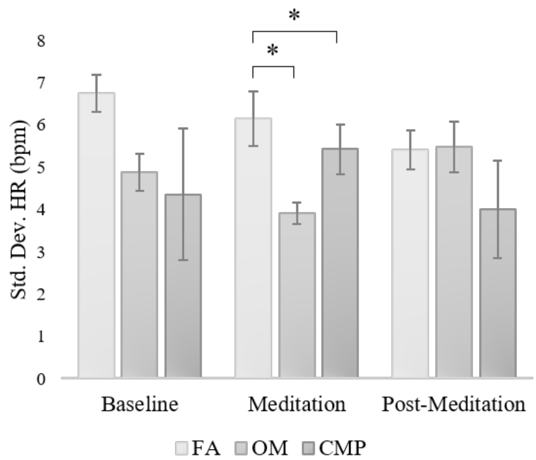


Figure 3.40: Standard deviation of the HR for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods. The * indicates significant differences with p $\leq$ 0.05.

The standard deviation of the HR during the meditation period was significantly higher for the FA meditation practice in comparison to the OM meditation practice (p = 0.029) (Figure 3.40). Additionally, there was a significant difference between all meditation practices during the meditation period (p = 0.032).

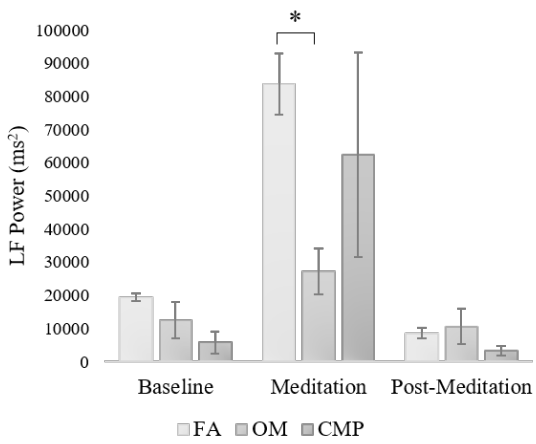


Figure 3.41: LF power for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$.

As shown in Figure 3.41, the LF power was significantly higher for the FA meditation practice when compared to the OM meditation practice ($p = 0.029$). There were no other significant differences between all practices and paired-practices.

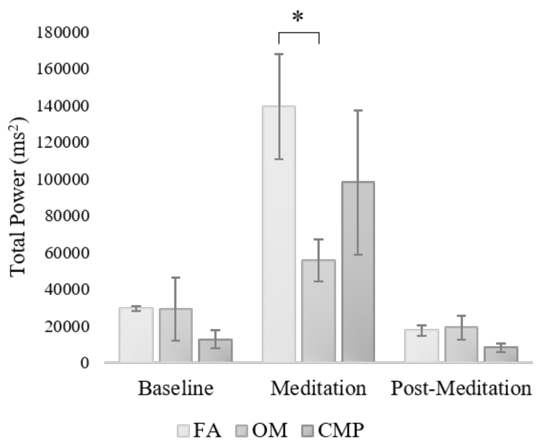


Figure 3.42: Total power for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$.

The total power of the HRV was significantly higher for the FA meditation practice in comparison to the OM meditation practice ($p = 0.029$) (Figure 3.42).

3.4 Frequency of Practice Analysis

The following section presents the results of the EEG and PPG signals for the daily and regular practices of meditation. Only the parameters that revealed significant statistical differences were shown in this section. The other results may be found in Appendix B.3.

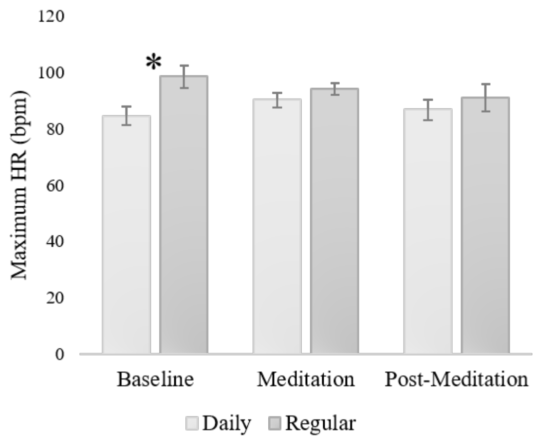


Figure 3.43: Maximum HR for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$.

As the Figure 3.43 shows, subjects with a daily practice of meditation revealed a significantly lower maximum HR value in comparison the ones with a regular practice during the baseline period ($p = 0.038$).

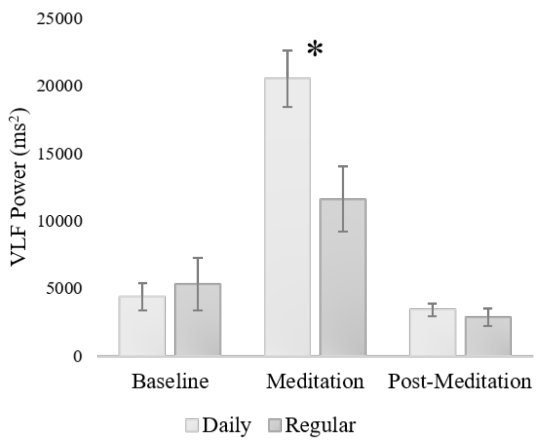


Figure 3.44: VLF power for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$.

Subjects with a daily practice of meditation revealed a significantly higher VLF power during the meditation period in comparison to the regular practitioners ($p = 0.038$) (Figure 3.44).

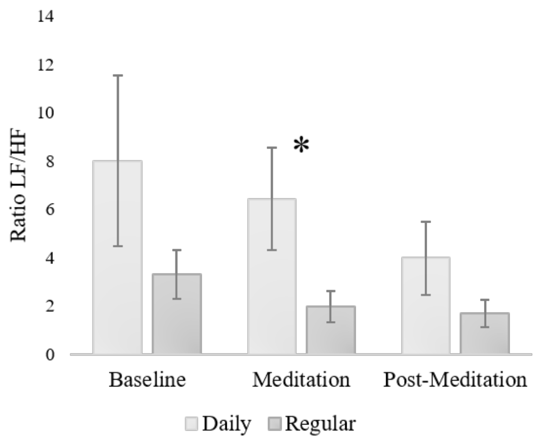


Figure 3.45: Ratio LF/HF for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$.

The LF/HF ratio was significantly higher for the subjects with a daily practice of meditation in comparison to the subjects with a regular practice during the meditation period ($p = 0.038$) (Figure 3.45).

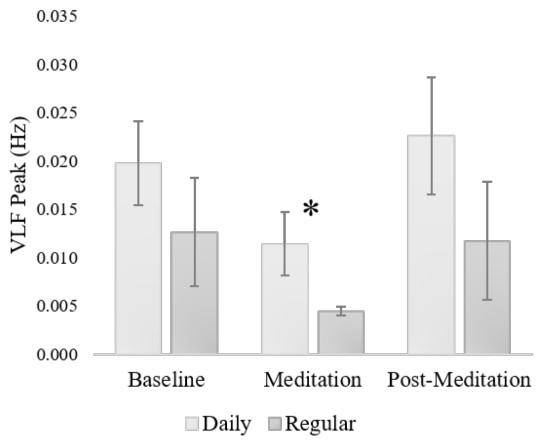
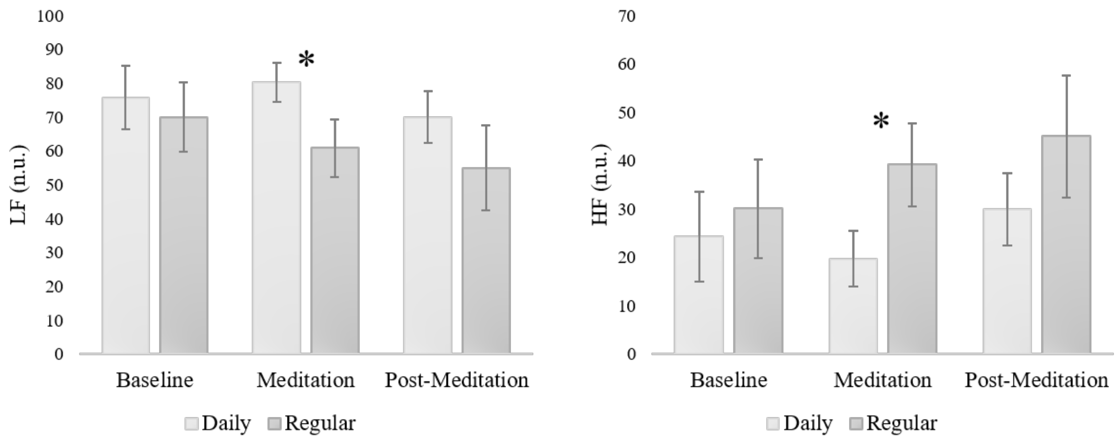


Figure 3.46: VLF peak for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$.

As shown in Figure Figure 3.46, subjects with a daily practice of meditation showed a significantly higher VLF peak during the meditation period in comparison to the regular practitioners ($p = 0.019$).



(a)

(b)

Figure 3.47: (a) LF (n.u.) and (b) HF (n.u.) for the for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods. The * indicates significant differences with $p \leq 0.05$.

Subjects with a daily practice of meditation showed a significantly higher LF power (n.u.) when compared to the ones with a regular practice during the meditation period ($p = 0.038$) (Figure 3.47a). Similarly, subjects with a daily practice of meditation showed a significantly lower HF power (n.u.) in comparison to the subjects with a regular practice during the meditation period ($p = 0.038$) (Figure 3.47b).

Chapter 4

Discussion

In order to simplify the discussion of the results, this section will be divided into three main parts: differences between groups (meditator vs. control), differences between practices (FA vs. OM vs. CMP) and differences between the frequency of practice (daily vs. regular).

4.1 Differences Between Groups

To facilitate the systematization of the main differences of the EEG and PPG analysis, this section is divided into two parts: altered traits and altered states. The altered traits concern the differences between both groups during each separate period, and the altered states refer to the changes between pairs of periods, i.e. baseline vs. meditation, meditation vs. post-meditation and finally baseline vs. post-meditation. Each of them help evaluate the effects of meditation, the process of exiting a meditative state, and the effects generated during relaxation after a meditation practice, respectively.

4.1.1 Altered Traits

One of the most interesting results of the EEG analysis were the differences in the relative alpha power for the meditator group in each period in comparison to the control group. The meditator group showed consistently lower values in the left, right and combination of both hemispheres. These results are corroborated by another study, wherein the participants who received autogenic training revealed lower percent alpha power in comparison to another group which did not receive this training (Jacobs and Lubar, 1989). Although that study did not comprise a meditation practice per se, the basis of autogenic training is very similar to a practice found in Yogic traditions called *yoganidra*. This technique is commonly performed by yogis after the practice of *asana* (which are the physical postures of *yoga*), and aims at directing attention to a specific part of the body, while emphasising relaxation, and in consequence achieve deep relaxation. In the present study, the meditator group also revealed a lower alpha/beta ratio during the baseline period in comparison to the control group. As mentioned before, the alpha/beta ratio provides information about the evolution of the cognitive state as well as the fatigue and tiredness (Eoh et al., 2005, Jap et al., 2009). Thus, higher values of this ratio may indicate higher levels of fatigue.

4. DISCUSSION

Since the values of the alpha/beta ratio were lower for the meditator group during baseline, it is possible to infer that this group showed lower levels of fatigue in comparison to the control group. These differences between groups in the relative alpha power and alpha/beta ratio may be interpreted as possible trait changes, in which a continued meditation practice throughout time can result in a decrease of the relative alpha power and beta/alpha ratio.

The PPG findings were the most interesting ones by far, and include: shorter RR-intervals (for each period), higher HR (for each period), higher standard deviation of the HR (except for the meditation period), higher maximum HR (for each period), higher LF power (except for meditation period), higher LF/HF ratio (for each period), higher LF (n.u.) (for each period), lower HF (n.u.) (for each period) and lower BR (except for meditation period). The average duration of the RR-intervals were consistently lower during all three periods for the meditators in comparison to the control group. Thus it is possible to conclude that meditators tend to have smaller intervals between consecutive heartbeats. The average of the RR-interval is proportional to the HR, and as a result, lower RR-intervals translate in higher HR values. This is proven by the fact that the meditator group also showed a higher HR during each period in comparison to the control group. The PNS is usually responsible for decreasing the HR, which results in longer RR-intervals. As a result, the control group showed higher PNS activation during baseline and post-meditation periods, whereas the meditator group revealed greater SNS activation. The HR results were unexpected, since meditation research typically reports lower HR values during meditation, as well as during a baseline period (Khalsa et al., 2015, Telles et al., 2004). Telles et al. reported that after a 30-day *yoga* program, participants were able to significantly reduce their HR during a baseline periods, whereas the control group (which did not completed the program) were not able to reduce it (Telles et al., 2004). The standard deviation of the HR was also significantly higher for the meditator group during the baseline and post-meditation periods (the relaxing condition) in comparison to the control group. It is still unclear whether this measure is an accurate tool to evaluate HRV, since many other effects arising from the neurohormonal systems may contribute to HRV (Moser et al., 1994). However, such measure may indicate that the variability of the heart is higher for the meditation group during relaxed states (and even in normal everyday situations). Interestingly, the meditator group showed on average 1.22, 1.14 and 1.21 times higher maximum HR values during baseline, meditation and post-meditation periods, respectively. Additionally, the meditator group revealed higher LF power during baseline and post-meditation periods. This measure includes both information about the SNS activity and vagal modulation. In addition, the LF/HF ratio was also significantly higher for the meditator group during each period. This ratio represents the sympathovagal balance, so higher values represent greater SNS activity. The LF (n.u.) and HF (n.u.) were higher and lower for the meditator group, respectively, during each period, which provide an index of modulation of the SNS and PNS. As such, the meditators revealed a higher activation of the SNS and inhibition of the PNS system in comparison to the control group. This results of the LF (n.u.) and HF (n.u.) combined with the LF power and LF/HF ratio might explain why the meditator group showed consistently higher HR, since the PNS activity (which usually decreases HR and is represented by the HF component) was generally lower for this group as well. Finally, and one of the most interesting outcomes, was the average BR which were lower for the meditator group during baseline period. The present study goes in line with previous research which reported that long-term meditators showed slower respiration rate than controls (Wielgosz et al., 2016).

4.1.2 Altered States

4.1.2.1 Baseline vs. Meditation

The main alterations for the meditator group during the meditation period in comparison with the baseline period were: increase in relative delta power (except for the left hemisphere), decrease in absolute theta power (except for the right hemisphere), decrease in absolute alpha power (for all locations), decreases in absolute and relative beta power (for the combination of both hemispheres), absolute beta power (except for the left hemisphere) and relative beta power (for the right hemisphere), decrease in absolute total power (except for the right hemisphere), decrease in beta/(alpha + theta) ratio (for the combination of both hemisphere), increase in theta/beta ratio (except for the left hemisphere) and decrease in arousal. However, the majority of these changes were not exclusive for the meditators, and the control group also showed a decrease in theta absolute power (except for the left hemisphere), decrease in absolute alpha power, decrease in absolute beta power and decrease in relative beta power (except for left hemisphere), decrease in total absolute power, decrease in beta/(alpha + theta) ratio (except for the left hemisphere), increase in theta/beta ratio (except for the left hemisphere), increase in alpha/beta ratio (except for the left hemisphere) and decrease in arousal. The only specific alteration for the meditator group was the decrease in the absolute theta power in the left hemisphere. In general, the majority of these decreases in absolute power seemed to be more significant for the left hemisphere and for the combination of both hemispheres. The right hemisphere mainly revealed alterations for the control group. Interestingly, the relative power analysis revealed more significant changes for the right hemisphere and for the combination of both hemispheres.

The decrease in theta activity during meditation practices has been reported by other authors, although the majority of the studies report an increase in its activity (Dunn et al., 1999, Huang and Lo, 2009, Yu et al., 2011). A study which compared mindfulness and concentrative meditation practices, reported that the average theta amplitude was higher during the resting condition, in comparison to both meditation practices (Dunn et al., 1999). Additionally, experienced Zen meditation practitioners have shown a decrease in absolute and relative theta power during a meditation period in comparison to a resting control group (Huang and Lo, 2009). However, the condition for both groups were different, and the meditator group was performing a meditation practice whereas the control group remained in a resting condition. More recently, another research performed on novice Zen meditation practitioners (with focus on breathing), reported a decrease in the theta band activity as well as an increase in alpha activity (Yu et al., 2011). The present study goes in line with these other studies mentioned, in the sense that it also revealed a decrease in absolute theta activity during the meditation practice period, although this difference was observed for both groups. With that being said, this might occur due to meditation practice, whether in an experienced or inexperienced group.

The absolute alpha power decreased for all locations, i.e. left, right and combination of both hemispheres. Although increases are more commonly reported, some authors have also came across opposite outcomes. Decreases in alpha activity have been observed during *kriya yoga*, which may involve breathing exercise (i.e. *pranayama*), as well as transcendental meditation (Das and Gastaut, 1957, Pagano et al., 1976).

Both absolute and relative beta power decreases occurred during the meditation period. Other authors reported similar results during self-regulation and relaxation response (Ikemi, 1988, Jacobs et al., 1996). However, those studies did not concern meditation practices per se, and the first was based on autogenic training and Zen meditation, and the last one shared common basis with OM techniques, in which the subject engages in a repetitive mental activity and ignores distracting thoughts. The self-regulation method research found decreases in relative beta power, whereas the relaxation response reported decreases in absolute power. The present study goes in line with both of them.

The only significant increases for the meditator group, although not exclusive, were in the delta relative power and in the theta/beta ratio (except for the left hemisphere, for both cases). Increases in the delta activity have also been reported at frontal regions during *vipassana* meditative practice (in which the mindfulness was based) (Cahn et al., 2010). Other studies performed in experienced Zen and Qi-Gong meditators have shown that an increase in frontal delta activity may be related with meditation, since it is associated with the reduction of emotional and cognitive engagement, providing an indicator for greater detachment (Faber et al., 2008, Tei et al., 2009). In the present study, only relative delta power increased during meditation, however it may indicate a possible shift in brain function, in which the brain shapes itself to become less disturbed, i.e. more detached. In addition, the theta/beta ratio, which is involved in cognitive and attentional tasks, also increased during meditation, so this may be interpreted as an increase in levels of attention. These information combined may represent an attentive yet detached state of the brain for the meditator group, whereas for the control group it may represent an overstimulated and disturbed mind.

The total absolute power showed an overall decrease during meditation, which may indicate that meditation practice produces a decrease in brain power. The beta/(alpha + theta) ratio, which provides an estimation of mental effort or engagement, decreased during the meditation period for both groups. However, for the meditators this result may indicate an increase in detachment, whereas for the control group it may be interpreted as an increase in distraction, or difficulty in maintaining focus on a specific task (i.e. breathing). Additionally, the $log(alpha_{right}) + log(alpha_{left})$, or arousal, also showed a decrease between the baseline and meditation periods, for both groups. This may indicate that the meditative experience resulted in a decrease in arousal, although increasing the levels of attention.

Regarding the PPG results, the main findings between the baseline and meditation periods were: increase in maximum HR (for the control group), increase in VLF power (for both groups), increase in LF power (for both groups), increase in HF power (for both groups), increase in total power (for both groups), decrease in VLF peak (for the meditator group) and decrease in average BR (for the control group). The increase in the maximum HR between baseline and meditation may indicate that the meditation practice for the control group was in fact a stressful task. It may represent the effort required by this group in order to continuously be aware of their respiration. The increase in VLF, LF and HF powers by both groups may provide information about the overall activation of the ANS during meditation practice. However, it should be noted that the baseline task only evaluated a total period length of 115 s, which is in fact a very short period. Usually, the recordings should be at least 10 times the wavelength of the lowest limit of the component of interest, which is approximately 50, 4 and 1 min for the VLF, LF and HF components. As a result, only the HF frequency component meets this criteria, and as such provides a trustworthier result. Since this measure increased during meditation, it reveals that the meditation practices for both groups resulted in an activation of the PNS or greater vagal activity. Usually, lower HF power values are associated with stress and anxiety, so meditation practice may in fact reduce their symptoms. The VLF peak decreased during meditation for the meditator group, which means that the highest PSD value was found in lower frequency values of the VLF band. The implications of the VLF component are not well known, however it has been proposed to be involved in thermoregulation (Taylor et al., 1998). In addition, the validity of this component in the present study is somewhat questionable, since the baseline period only compromised a total of 115 s. The VLF band was also evaluated during concentrative meditation, in which the authors mentioned that the *samadhi* state might be characterized by the appearance of LF, HF or VLF-resonant peaks (Phongsuphap et al., 2008). However, the results showed the resonant peak in the VLF component was rare. Finally, the control group presented lower BR during meditation, which was somewhat expected since the BR is very easily decreased once one brings awareness to it. The meditation practice for the control group was breath-oriented, so they were already aware to keep track of it. Nevertheless, higher BR values are associated with stress and anxiety, so a meditation practice with a focus on breathing could in fact help reduce their symptoms temporarily, i.e. immediately after its practice.

4.1.2.2 Meditation vs. Post-Meditation

Interestingly, the meditator group only revealed significant differences in the left hemisphere of the brain between meditation and post-meditation, such as: decrease in relative delta power, increase in relative beta power, increase in beta/(alpha + theta) ratio and decrease in theta/beta ratio. For the control group, the most relevant differences were more frequent in the right hemisphere and combination of both hemispheres, and were decreases in: absolute delta (except for the left hemisphere), absolute theta power, alpha absolute power (except for the left hemisphere), relative theta power (for the combination of both hemispheres), theta/beta ratio and arousal. In summary, the meditator group mainly revealed difference in the relative power, whereas the control group showed differences in the absolute power. Since the meditator mainly showed significant differences in the relative band power, this might indicate that meditation does in fact cause shifts in brain function. The relative delta power decreased between meditation and post-meditation periods, counteracting the effects caused by meditation (which provoked an increase). The same goes with the relative beta power. With this being said, meditation practice is indeed different than a relaxation task, since meditation caused an increase in relative delta power and a decrease in relative beta power, and the relaxation task caused the opposite effect, i.e. decrease in delta and increase in beta relative powers. The same logic might be applied for the beta/(alpha + theta) and theta/beta ratios. It is to note a curious result, which is that entering in a meditative state mainly showed differences in the relative power for the right hemisphere and combination of both hemispheres, whereas the exiting of that state (and transition to relaxation) mostly evidenced differences in the relative power for the left hemisphere.

The main PPG findings were: increases in the minimum HR (for the meditator group), VLF peak (for the meditator group), and decreases in the average HR (for the control group), VLF power (for both groups), LF power (for both groups), HF power (for both groups) and total power (for both groups). In general, the meditator group presented the most significant changes between the meditation and post-meditation periods. A possible explanation might be that the meditator group are more used to a post-meditation relaxation task, since many meditation practices end with some form of relaxation or insight period. The decrease in the average and standard deviation of the HR for the control group does provide an interesting result. This suggests this group was in fact in great effort during the meditation period, and when it ended, they experienced some kind of relief. Once again, the validity of VLF and LF powers are questionable, since the post-meditation period only considered a time length of 100 s. However, the HF band does provide useful information since the period is over 1 min, and with that it is possible to mention a further decrease in its power, possibly indicating a deactivation of the PNS once again for both groups.

4.1.2.3 Baseline vs. Post-Meditation

The main differences between the baseline and post-meditation periods for the meditator group were decreases in absolute theta power (except for the right hemisphere), absolute alpha power (except for the left hemisphere) and arousal. Whereas for the control group, the main findings were decreases in absolute theta power, absolute alpha power, absolute beta power (except for the left hemisphere), absolute total power (except for the left hemisphere), arousal and an increase in relative delta power (for the right hemisphere). Both groups seemed to endure the changes caused by meditation. The decrease in arousal for both groups provides an idea that meditation may in fact be helpful for stress and anxiety reduction.

For the PPG analysis, the main findings were decreases in the LF power (for both groups) and LF/HF ratio (for the meditator group). It seems that meditation practice caused a decrease in the SNS activation during the final relaxation period, in comparison to the first one.

4.2 Differences Between Practices

In general, the comparison between practices, whether all three of them together or in paired conditions, did not show many significant differences for the EEG. However, the ones that did occur during the baseline period were: relative theta power for the left hemisphere (FA vs. OM), relative alpha power for the right hemisphere (between all three practices and FA vs. OM) and relative alpha power for the combination of both hemispheres (FA vs. OM) . A comparison between mindfulness and concentrative meditation practices showed higher theta and alpha amplitudes for the mindfulness practice (Dunn et al., 1999). The present study is in agreement with these results, since the FA meditation practice, which would be equivalent to the concentrative meditation practice, showed lower theta and alpha relative powers than the OM meditation practice, which would be equivalent to the mindfulness practice. However, these differences were not significant during the meditation period, but rather during the baseline period, possibly indicating that the preparation for both practices produces different outcomes.

The PPG analysis mainly showed differences during the meditation period in: SDNN (FA vs. OM), standard deviation of the HR (between all three practices and FA vs. OM), LF power (FA vs. OM) and total power (FA vs. OM). Interestingly, there were no significant differences in both the average HR and RR-interval between the different meditation practices. A study by Lumma et al. reported that the HR was increased in loving-kindness meditation and observing thoughts meditation in comparison to a breathing type meditation, which translates into the CMP, OM and FA categories in the present study (Lumma et al., 2015). In fact, during the meditation period, the CMP practice produced on average higher HR values, followed by FA and OM meditation practices, although the differences were not significant. However, the standard deviation of the HR was significantly different between all three meditation practices, and between FA and OM practices as well during the meditation period. The FA meditation showed on average HR values 1.03 times higher than the OM meditation. This might be explained by the fact that FA practitioners were the least experienced group (418.5 ± 567.9 h), and as result experienced more effort during the meditation practice, increasing the standard deviation of the HR. The OM group was the most experienced one (2631.3 ± 3400.2 h), probably explaining why they showed the lowest values, followed by the CMP group (958.0 ± 958.0 h). The LF power was higher for the FA meditation practice in comparison to OM, which may indicate an increase in SNS activation.

4.3 Differences Between Frequency of Practice

The frequency of meditation practice showed no significant differences for the EEG analysis. This is not surprising since both subgroups did in fact endure a continued meditation practice, whether on a daily (i.e. everyday of the week) or a regular (i.e. between 3–4 days a week) basis, and its difference would not be substantial. However, those who were on a daily basis practice showed an overall decrease in absolute power (except for the left hemisphere), decrease in relative power (except for beta and gamma bands), increase in beta/(alpha + theta) ratio, decrease in theta/beta ratio as well as decrease in alpha/beta ratio.

The only significant changes between subgroups were found in the PPG analysis, and were: lower values of maximum HR during baseline, higher values of VLF power, LF/HF ratio, VLF peak and LF (n.u.) during meditation and lower HF (n.u.) during meditation for the daily practitioners of meditation. It is not a surprise that daily practitioners exhibit a higher experience in meditation (1992.3 ± 2820.7 h) than the regular practitioners (981.3 ± 491.0 h). Interestingly, the maximum HR during the baseline period for the daily meditation practitioners was lower in comparison to the regular practitioners. Higher values of the resting HR can be a marker for an increased risk of cardiac disease, so practitioners might in fact benefit even more with a daily practice of meditation. The VLF power was higher for the daily practitioners during meditation. Lower values of VLF power has been associated with arrhythmic death and high inflammation, as already mentioned (Bigger Jr et al., 1992, Carney et al., 2007). In addition, the LF/HF ratio was also higher during meditation for the daily practitioners, which possibly indicates greater SNS activation. However, the daily subgroup contained 2 FA, 2 OM and 2 CMP meditation practitioners, whereas the regular subgroup only contained 2 FA and 2 OM practitioners. Evidently, these practices have different effects on the ANS, so it is not possible to make any valid conclusion for the VLF power and LF/HF ratio. The same applies to the VLF peak, LF (n.u.) and HF (n.u.).

4.4 Limitations

There are several limitations in the present study. The first one is the small sample size, containing a total of only 19 participants (10 meditators and 9 non-meditators). Additionally, it was not possible to match both sex and age of the meditator group, mainly due to the Covid-19 pandemic, which resulted in an added difficulty in finding adequate controls who were interested in participating in the study. A further limitation of this study was the variety of meditation practices in the meditator group. However, this was somewhat expected, since the interest in this study was to evaluate the meditation practice in which the participant felt more familiarized with. The way found to deal with this limitation was the categorization of the meditation practices into one of the three categories. Within the meditator group, there were only 4 OM, 4 FA and 2 CMP practitioners, which might be the reason why the comparison of practices did not reveal many significant differences. In addition, the acquisition of the physiological signals were in a non-laboratory setting and different for each subject. The main reason behind this was to allow the participants to choose a place in which they felt most comfortable and familiarized with, and in that way make the acquisition the more natural as possible. In addition, the periods evaluated did not have the same duration, and the meditation period was much longer than the baseline and post-meditation periods. It might have been better to compare the differences in periods with the same duration, however that would either result in some disadvantages for the PPG frequency domain analysis, or longer baseline and post-meditation periods which would make the total acquisition procedure much longer and uncomfortable for the participants. Finally, the use of only two frontal electrodes does constitute a limitation of this study since additional information about the brain activity was not being measured.

Chapter 5

Conclusion

The results of the present study, within the limitations noted above, did show some interesting results. These include the differences between groups, which probably translates the altered traits in meditators, as a result of continuous meditation practice. Amongst them it is highlighted the baseline differences in BR, which was lower for the meditators group and is in accord with previous studies (Wielgosz et al., 2016). A slower BR is associated with less stress and anxiety, indicating that meditation practice may in fact help decrease its symptoms. The significantly lower alpha/beta ratio for the meditator group may also provide an indication for lower levels of fatigue during baseline. Additionally, the lower levels of relative alpha power observed during each period possibly refer to a shift in brain function for the meditators, and is in accord with a previous study (Jacobs and Lubar, 1989). Its decreased values may indicate that the meditators find it easier to relax, and perceive the relaxation and meditation periods with less effort. The decrease in the absolute theta, alpha and beta power during the meditation period have been reported by other authors during mindfulness, concentrative meditation, Zen, *kriya yoga*, transcendental meditation, self-regulation and relaxation response (Dunn et al., 1999, Huang and Lo, 2009, Yu et al., 2011, Das and Gastaut, 1957, Pagano et al., 1976, Ikemi, 1988, Jacobs et al., 1996). However, it is more commonly reported increases in these bands during meditation practice (Lomas et al., 2015). The increase in delta power has been observed during *Vipassana*, Zen and Qi-Gong, and it may be an indicator for greater detachment (Cahn et al., 2010, Faber et al., 2008, Tei et al., 2009). However, very few studies have analysed delta oscillations, so it is required further investigation in order to interpret their meaning (Lomas et al., 2015). The theta/beta ratio also increased during meditation periods, for both groups, nonetheless it may provide an index of distraction, however in a purposeful way for the meditator group. The present study also revealed a significant decrease during meditation in beta/(alpha + theta) ratio, which may provide an indication for detachment or purposeful distraction as well for the meditator group. The increase in alpha/beta ratio and average HR combined might be an indicator for greater effort during meditation, as observed in the control group. Additionally, the counteracting effects between the baseline/meditation and meditation/post-meditation periods help proving that meditation is in fact different from relaxation. These include the increase in the VLF, LF and HF power during meditation and decrease during the post-meditation period. Studies have reported increases as well as decreases during meditation practice in these measures; nonetheless it is difficult to interpret their meaning since the meditator group contained different practices which ultimately have different effects on the physiological signals (Phongsuphap et al., 2008, Amihai and Kozhevnikov, 2014, Amihai and Kozhevnikov, 2015, Léonard et al., 2019). It is highlighted the meditator group revealed higher LF component of the HRV possibly due to their slow breathing, since this component is highly affected by slow respiration rates. In regards with the different meditation practices, there were only few significant differences, possibly due to the small sample size. Nonetheless, FA meditation practices produced higher standard deviation of the HR during the meditation period, followed by CMP and OM. In order to properly investigate the differences between different meditation practices, larger samples should be considered. Finally, the daily meditation practitioners revealed lower values of the maximum HR during the baseline period in comparison to the regular practitioners. Typically, lower values of HR during rest are related with good health, whereas higher values might be an indicator for greater risk of cardiac disease, so a daily meditation practice might in fact help reduce this risk. However, the significant differences observed during meditation period for daily and regular practitioners did not allow for proper interpretation since each subgroup contained different meditation practices, which have different effects on the physiological measures. Thus, if the main goal of a study is to assess the differences between a daily and regular meditation practice, it should only be considered the same meditation practice.

The present study supports existing literature and advances the state of the art in which the combination of EEG and PPG signals, as well as the physiological measures mentioned above, may provide a powerful and useful tool to distinguish meditation practice from relaxation conditions. Nonetheless, further studies are required to better understand the implications of different meditation practices on the physiological signals.

To conclude, in the context of meditation it is important to mention intention as well. Meditation is a subjective experience, although its practice aims at the same principal goal, which is liberation of suffering, or enlightenment. However, it is subjective in the sense that the intention each practitioner places during each meditation practice may vary according to the different situations in life. In addition, meditation is an exercise like any other. Matthieu Ricard tells us that a successful meditation involves practice, or rather, a continued practice over time (Ricard, 2010). If a person only dedicates a certain amount of time to its practice, the benefits of them will come accordingly. Meditation is just like learning any other skill, such as learning how to read. If we only dedicate 5 min a day to learn how to read, we will need many more days to finish a book. The learning of meditation involves patience, and we should not be expecting anything miraculous to happen. Moreover, motivation is an important factor when learning meditation, and is one of the main reasons why so many people give up after a few tries. It is important to keep in mind that if we all dedicated more time to meditate than to the distractions surrounding us, we would all be more enlighten human beings.

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Appendix A

Questionnaire and Guided Meditation

A.1 Questionnaire

Sex:

☐ Male

☐ Female

☐ Other: ______________

Age: ______________

How long have you been practicing meditation? (Please answer in months or years)

____

How often do you practice meditation?

☐ Daily

☐ Regularly (a few times a week)

☐ Occasionally (a few times a week)

☐ Regularly (a few times a month)

☐ Rarely (a few days a year)

☐ Other: ______________

How long does your meditation practice last? (Please answer in minutes or hours)

____

What is your meditation school?

☐ Theravada

☐ Mahayana

☐ Vajrayana

☐ Mindfulness

☐ Yoga

☐ Does not apply

☐ Other: ______________

What is your most regular meditation practice?

☐ Focus on a single object (e.g. breathing)

☐ Focus on many points (e.g. bodily sensations)

☐ Mindfulness

☐ Compassion

☐ Transcendental (e.g. *mantra* based)

☐ Other: ______________

Please describe your meditation practice in detail.

____

____

____

____

Are you accompanied by a master/teacher?

☐ Yes

☐ No

What is the school of your master/teacher?

☐ Theravada

☐ Mahayana

☐ Vajrayana

☐ Mindfulness

☐ Yoga

☐ Does not apply

☐ Other: _______________

What is the experience of your master/teacher? (Please answer in years, if applied)

____

Have you ever attended a meditation retreat?

☐ Yes

☐ No

If applied, please indicate the number of retreats you have attended, the duration of each retreat (days / weeks / months / years and duration of meditation practice) and what type of practice in each retreat.

____

____

____

____

A.2 Guided Meditation

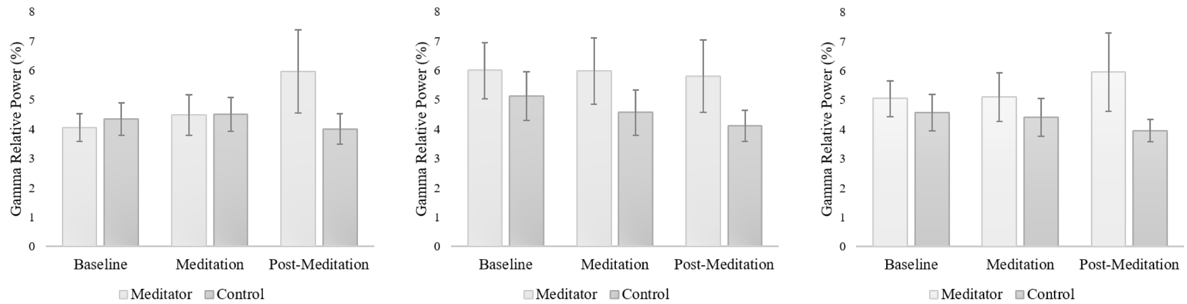
Breathing Focus Meditation

1. Start by sitting in a comfortable position
    a. If you can, bring the heel of your left leg close to the perineum, aligning the heel of your right leg with your left
    b. If you cannot do this, simply cross your legs in the most comfortable and natural way to you
2. Either place your palms on your knees, or the back of your right hand on top of your left palm, close to your abdomen
3. Keep your spine as straight as possible, gently bringing your shoulders back
4. Close your eyes
5. Take a deep breath in, and when you exhale, let go of the body and adjust your position if necessary
6. Try not to move a single part of your body from now on
7. Bring all your attention to your breath, to the air that enters through your nostrils, and to the air that comes out through your nostrils
    a. Pay attention to your breath, as it flows in and out of your body
    b. Pay attention to the sensations that the air causes when entering and leaving your body
8. If you feel your mind starts to wander, gently bring your attention back to your breath, without any judgment
    a. If it helps, you can count the number of breaths you take throughout this practice

Appendix B

Additional Figures

B.1 Group Analysis



(a) (b) (c)

Figure B.1: Relative power of gamma band for the meditator and control groups during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

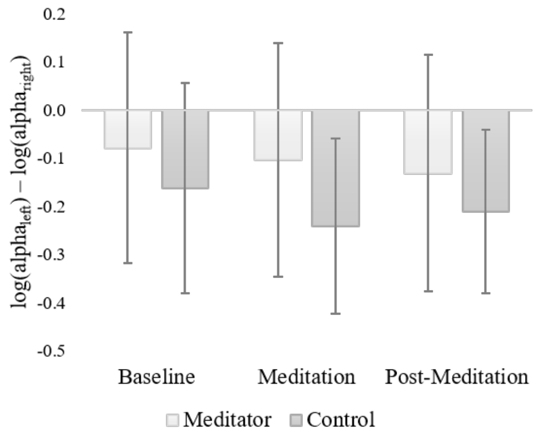


Figure B.2: Valence for the meditator and control groups during the baseline, meditation and post-meditation periods.

B. ADDITIONAL FIGURES

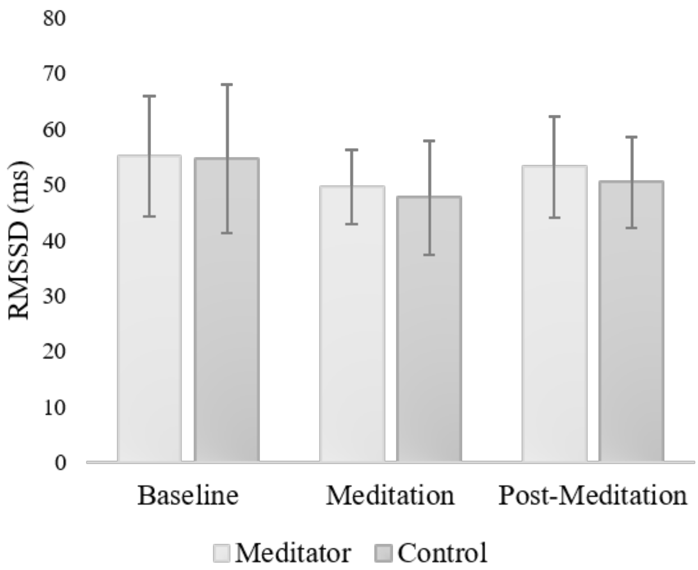


Figure B.3: RMSSD for the meditator and control groups during the baseline, meditation and post-meditation periods.

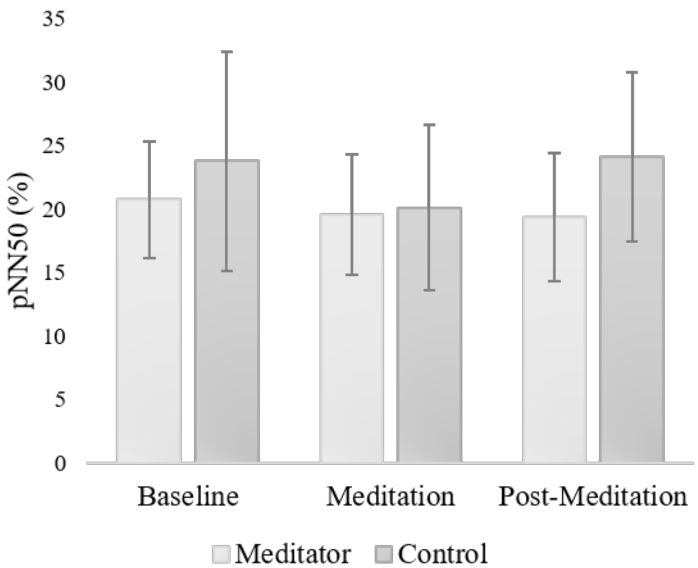


Figure B.4: pNN50 for the meditator and control groups during the baseline, meditation and post-meditation periods.

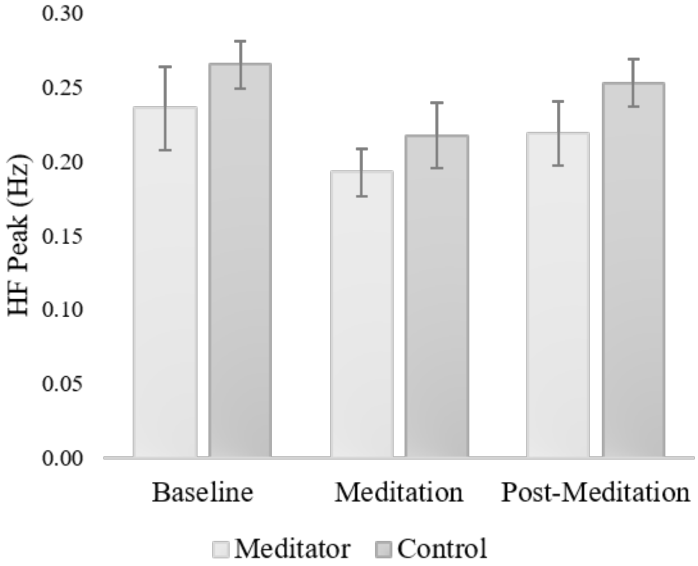
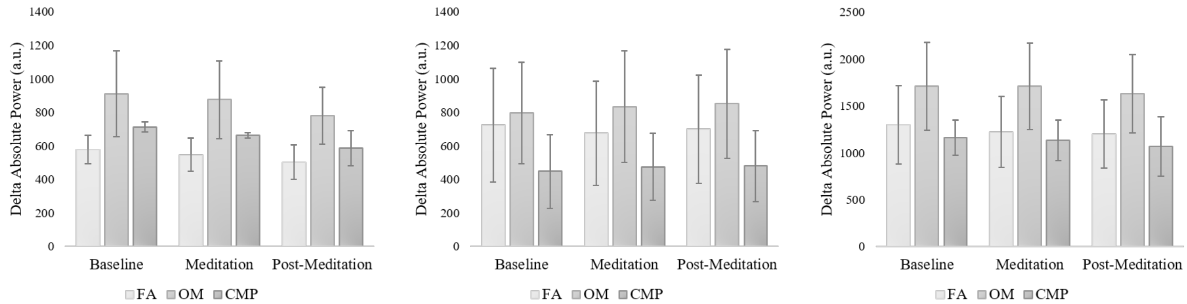


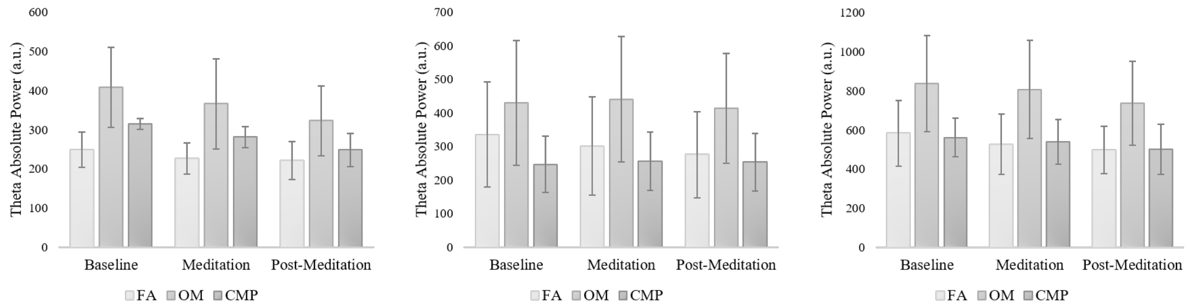
Figure B.5: HF peak for the meditator and control groups during the baseline, meditation and post-meditation periods.

B.2 Practice Analysis



(a) (b) (c)

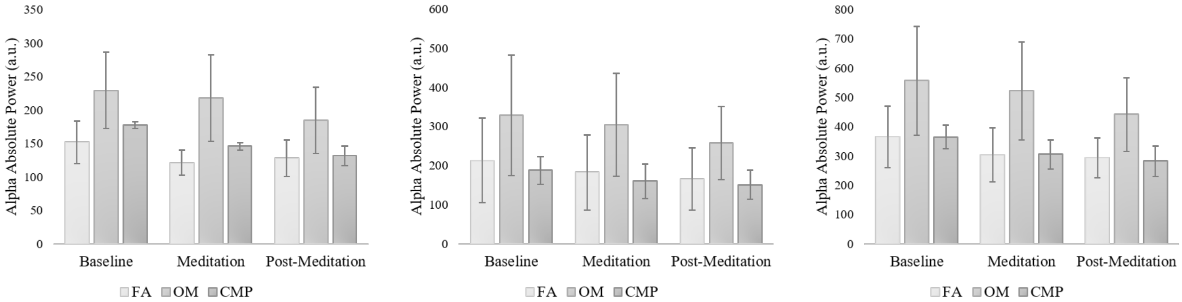
Figure B.6: Absolute power of delta band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

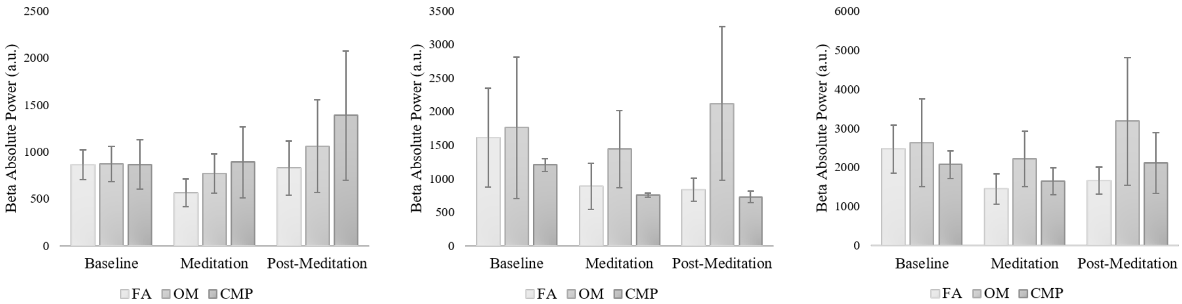
Figure B.7: Absolute power of theta band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

B. ADDITIONAL FIGURES



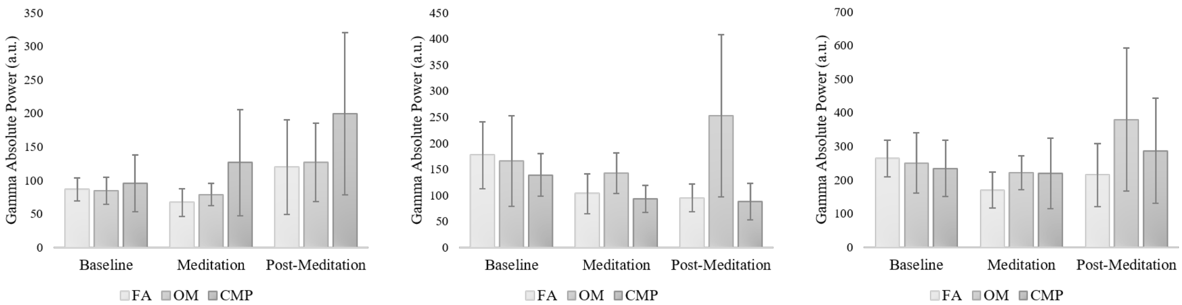
(a) (b) (c)

Figure B.8: Absolute power of alpha band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



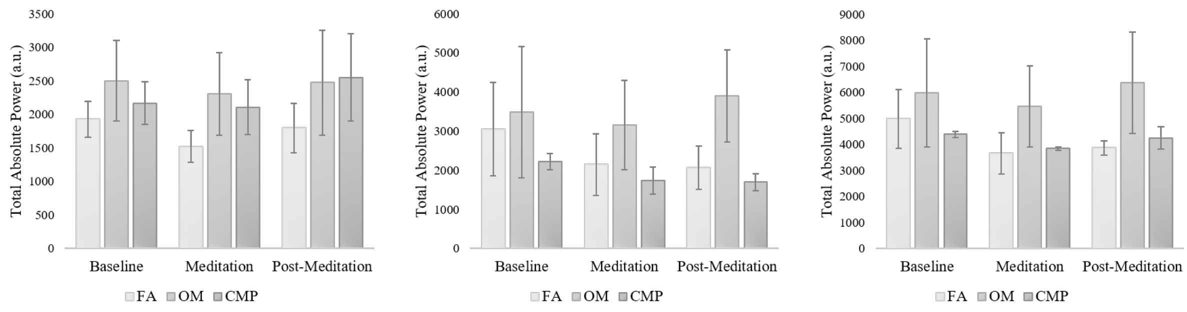
(a) (b) (c)

Figure B.9: Absolute power of beta band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



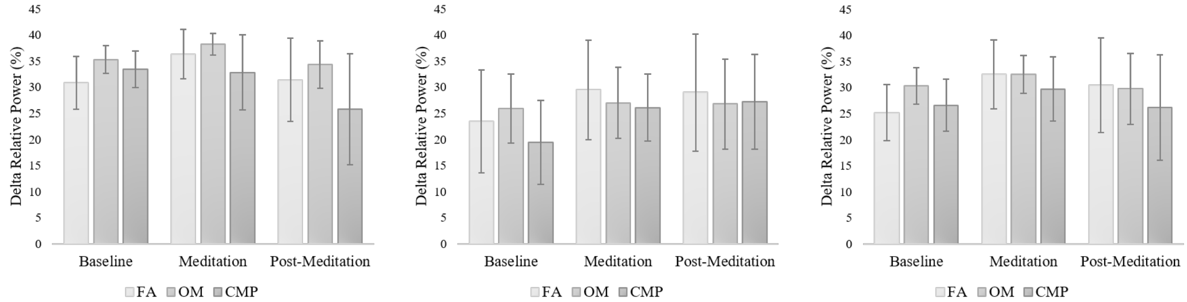
(a) (b) (c)

Figure B.10: Absolute power of gamma band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



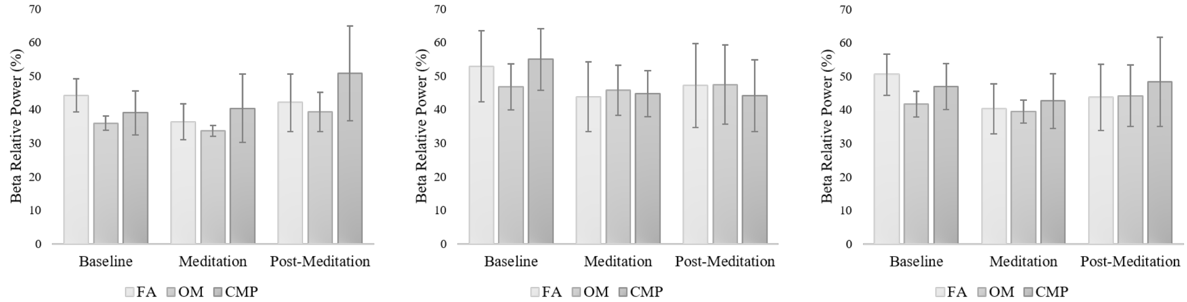
(a) (b) (c)

Figure B.11: Absolute power of all bands for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

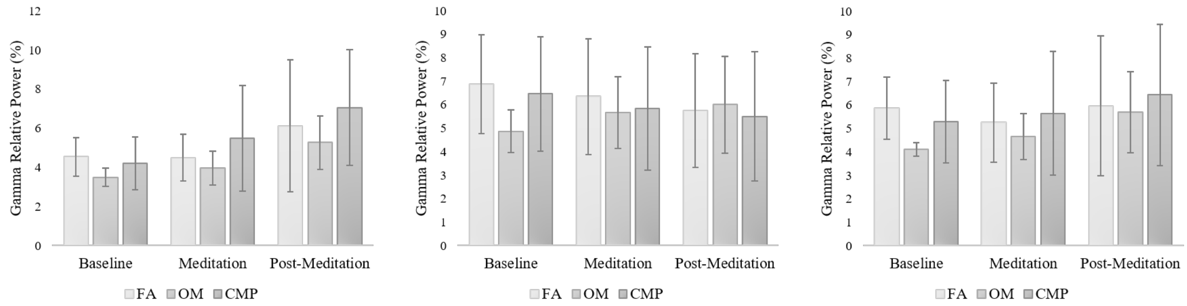
Figure B.12: Relative power of delta band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

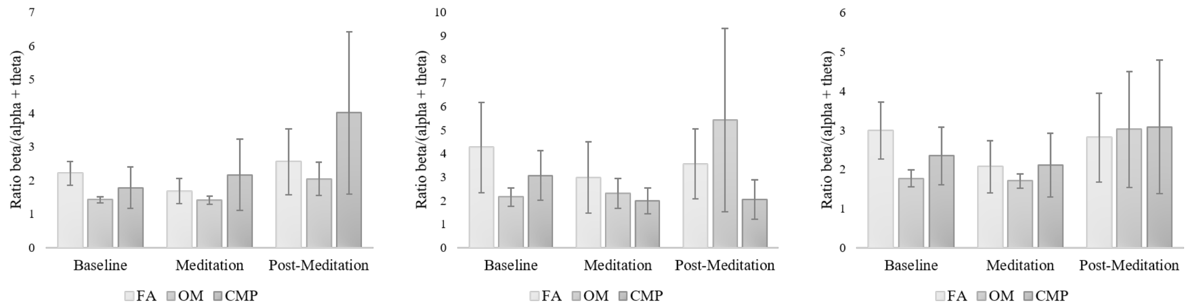
Figure B.13: Relative power of beta band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

B. ADDITIONAL FIGURES



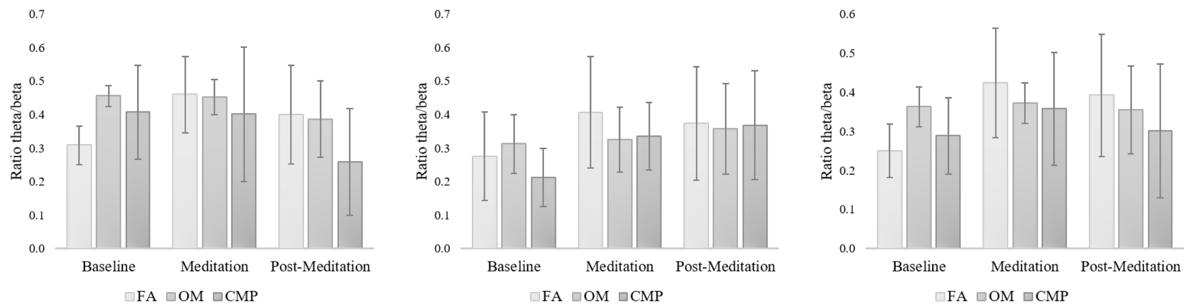
(a) (b) (c)

Figure B.14: Relative power of gamma band for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



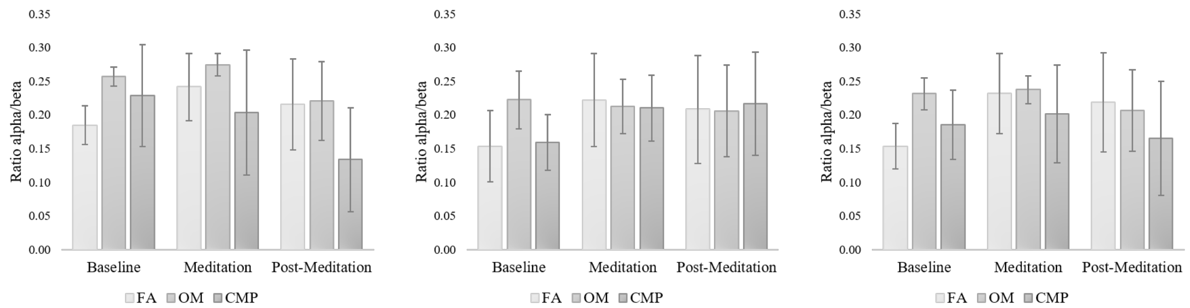
(a) (b) (c)

Figure B.15: Ratio beta/(alpha + theta) for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

Figure B.16: Ratio theta/beta for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

Figure B.17: Ratio alpha/beta for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

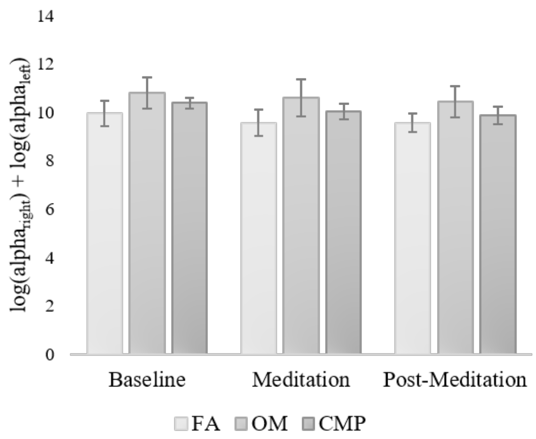


Figure B.18: Arousal for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

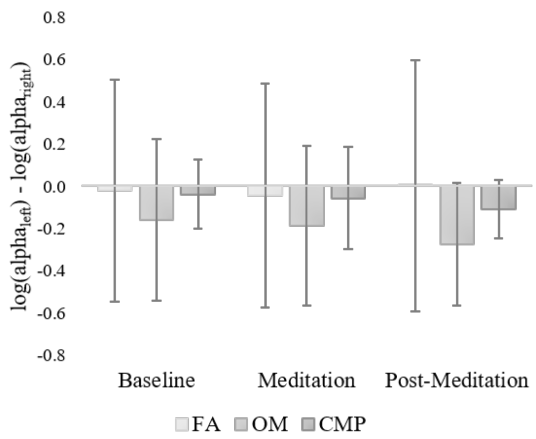


Figure B.19: Valence for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

B. ADDITIONAL FIGURES

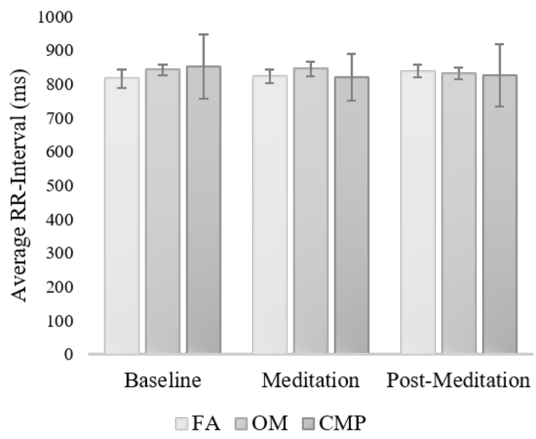


Figure B.20: Average RR-interval for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

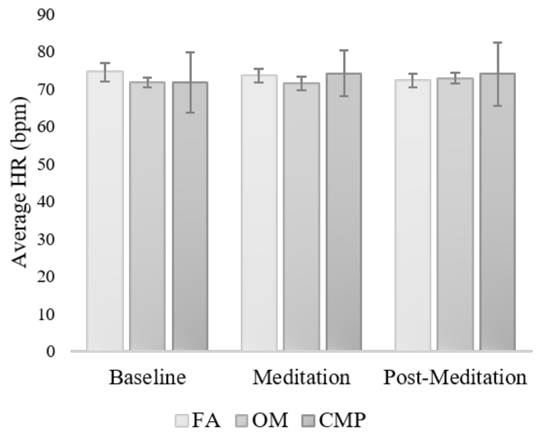


Figure B.21: Average HR for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

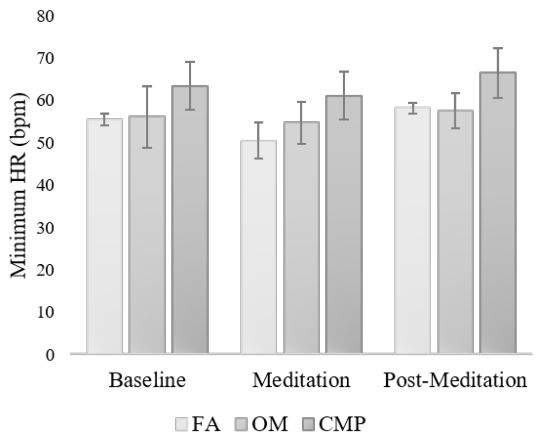


Figure B.22: Minimum HR for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

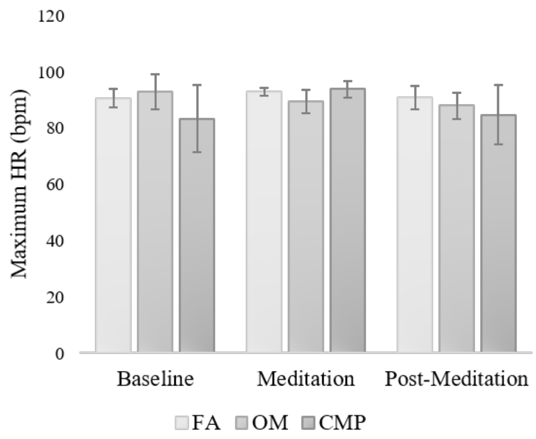


Figure B.23: Maximum HR for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

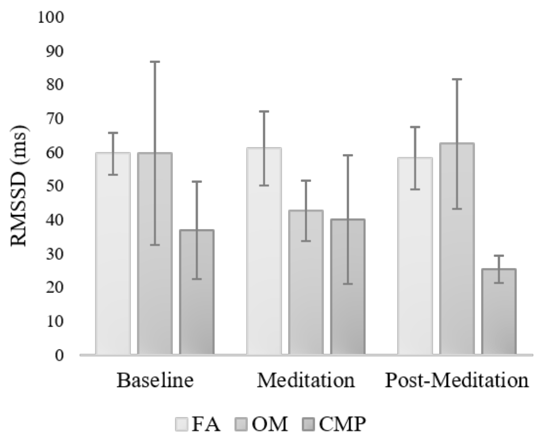


Figure B.24: RMSSD for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

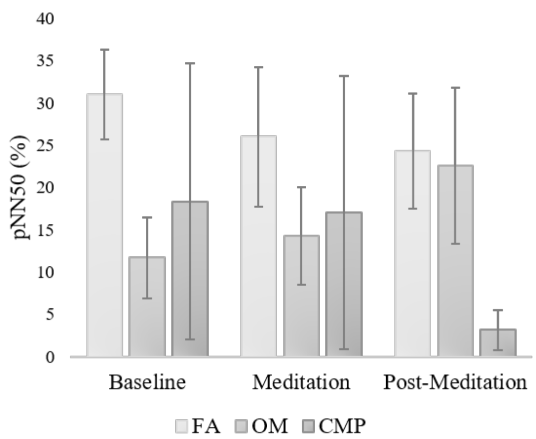


Figure B.25: pNN50 for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

B. ADDITIONAL FIGURES

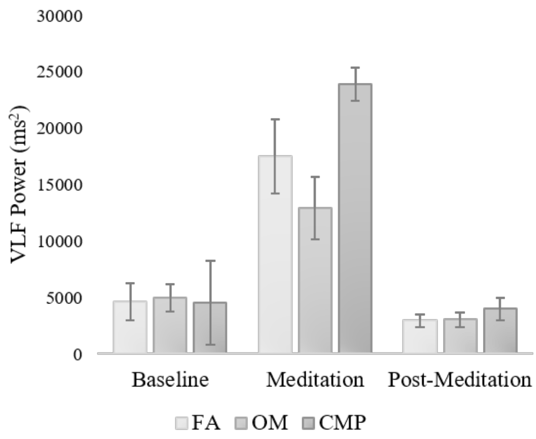


Figure B.26: VLF power for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

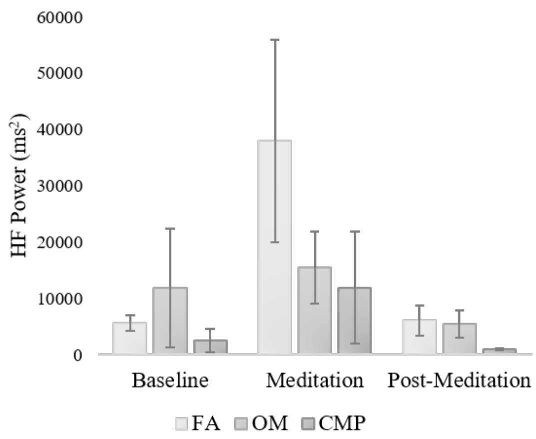


Figure B.27: HF power for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

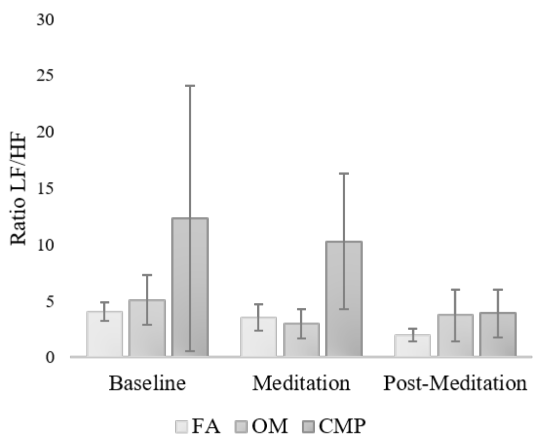


Figure B.28: LF/HF ratio for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

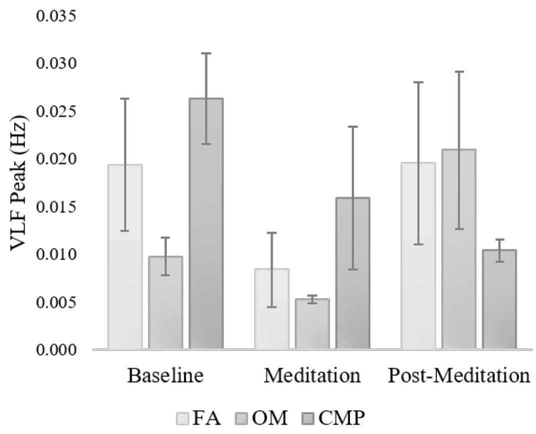


Figure B.29: VLF peak for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

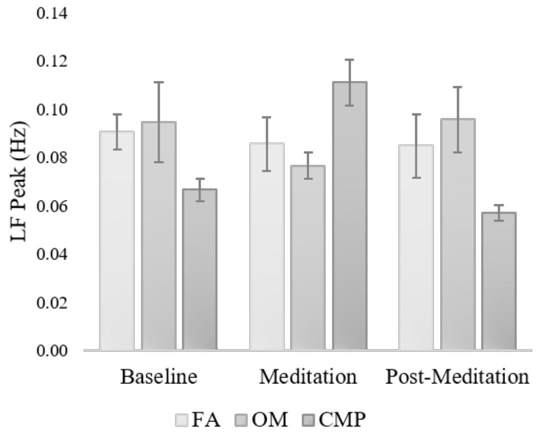


Figure B.30: LF peak for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

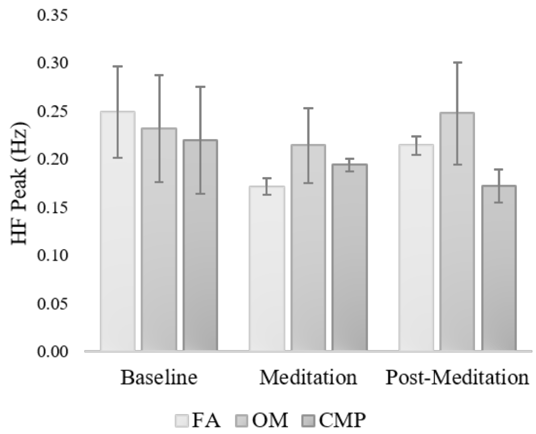


Figure B.31: HF peak for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

B. ADDITIONAL FIGURES

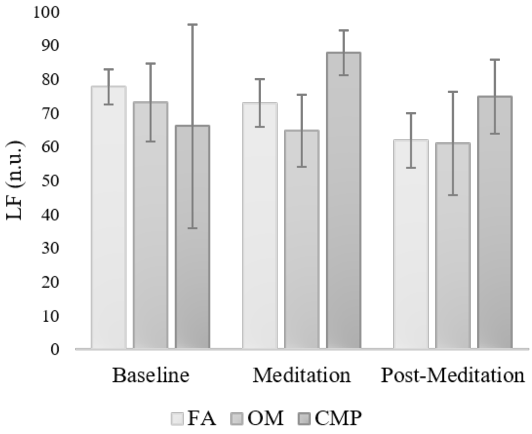


Figure B.32: LF (n.u.) for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

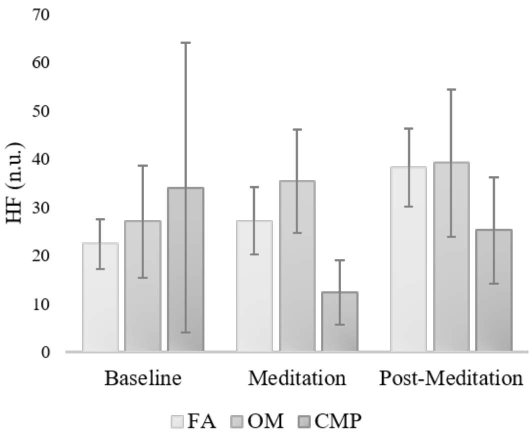


Figure B.33: HF (n.u.) for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

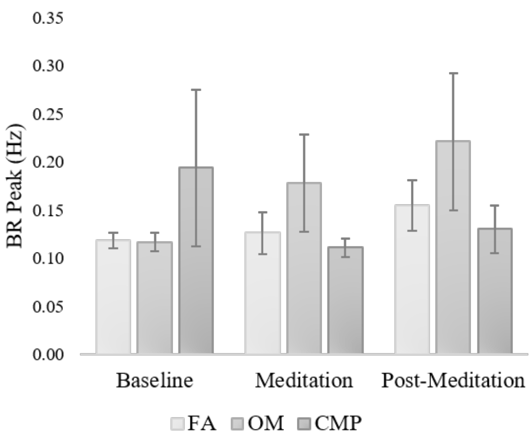
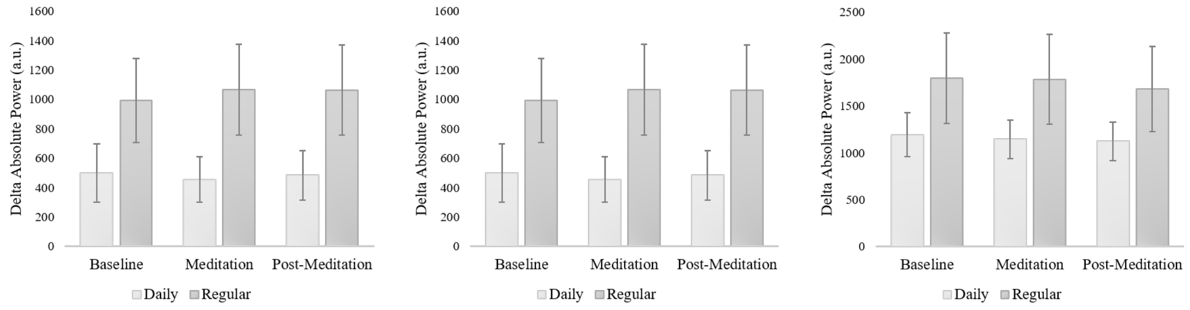


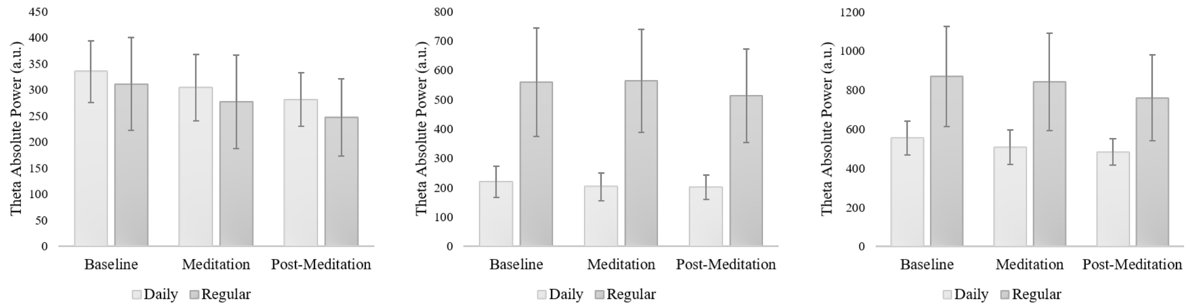
Figure B.34: Average BR for the FA, OM and CMP meditation practices during the baseline, meditation and post-meditation periods.

B.3 Frequency of Practice Analysis



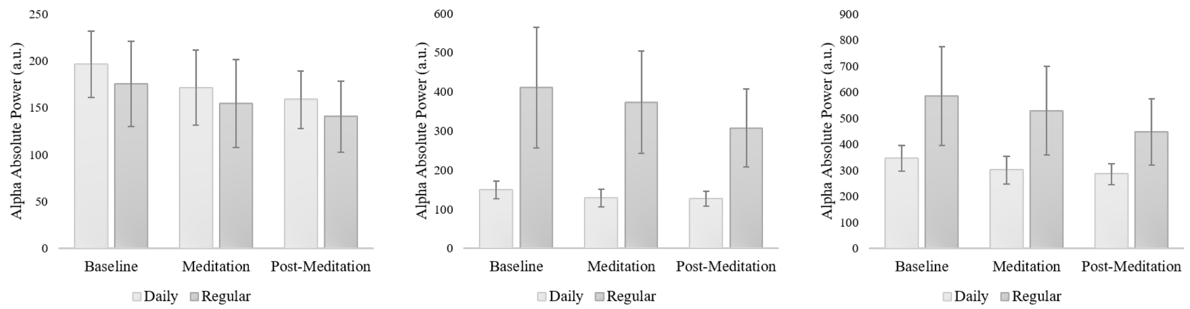
(a) (b) (c)

Figure B.35: Absolute power of delta band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

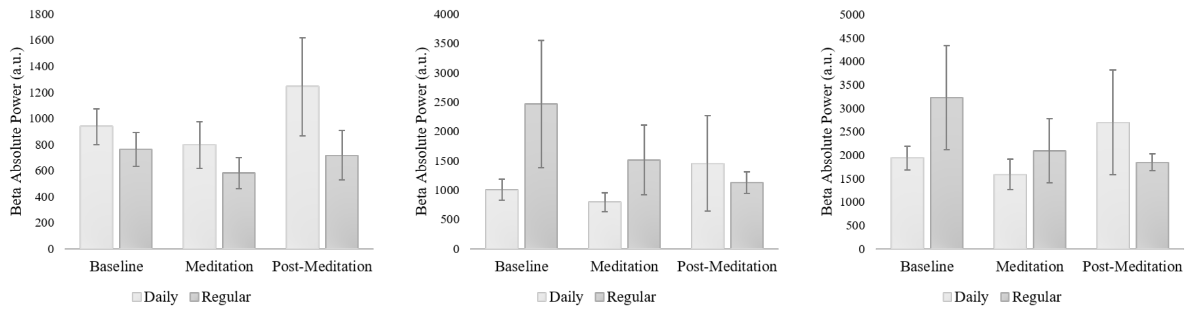
Figure B.36: Absolute power of theta band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

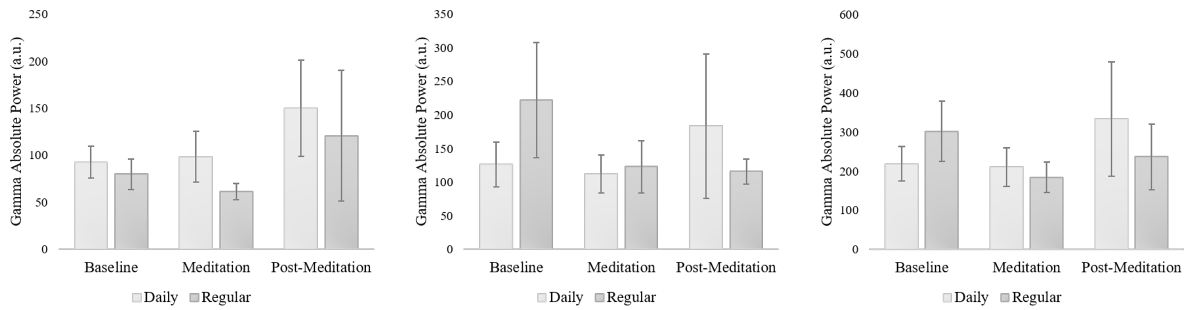
Figure B.37: Absolute power of alpha band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

B. ADDITIONAL FIGURES



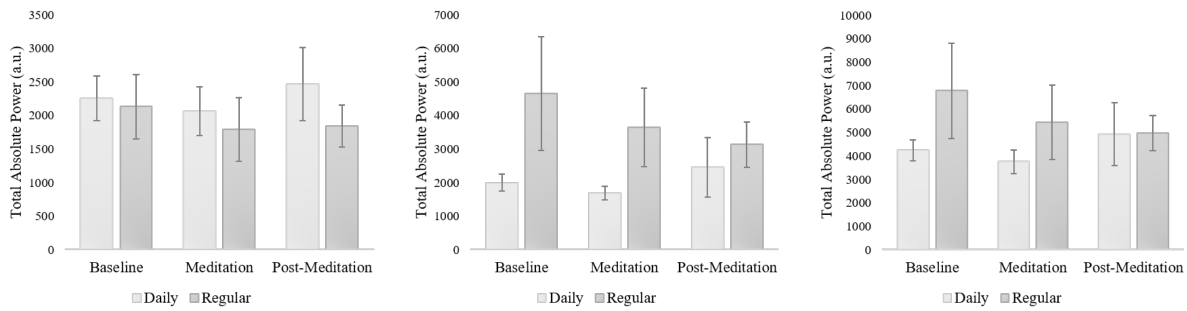
(a) (b) (c)

Figure B.38: Absolute power of beta band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

Figure B.39: Absolute power of gamma band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

Figure B.40: Absolute power of all bands for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

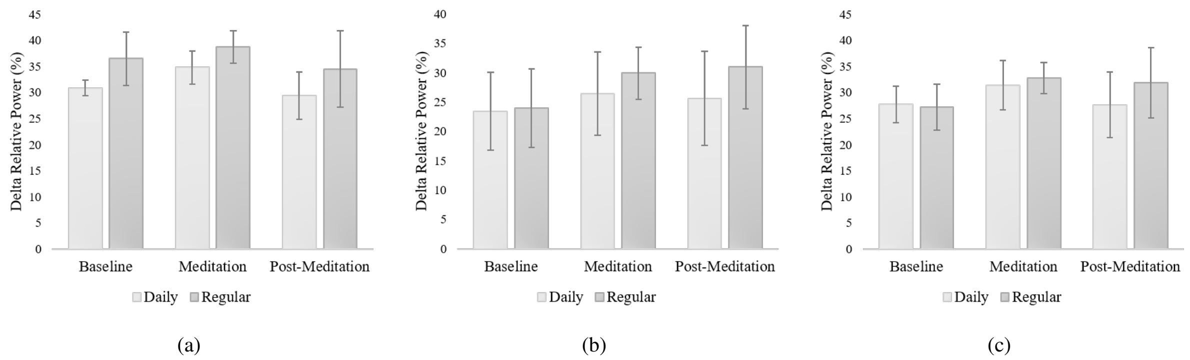


Figure B.41: Relative power of delta band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

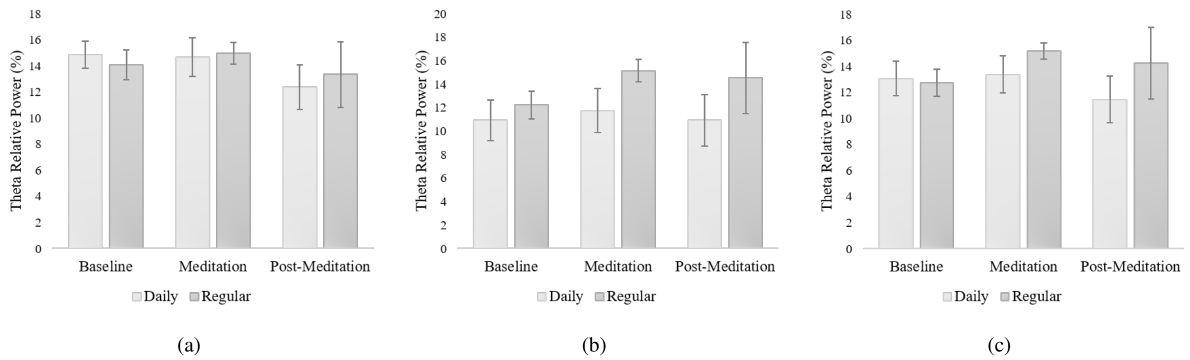


Figure B.42: Relative power of theta band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

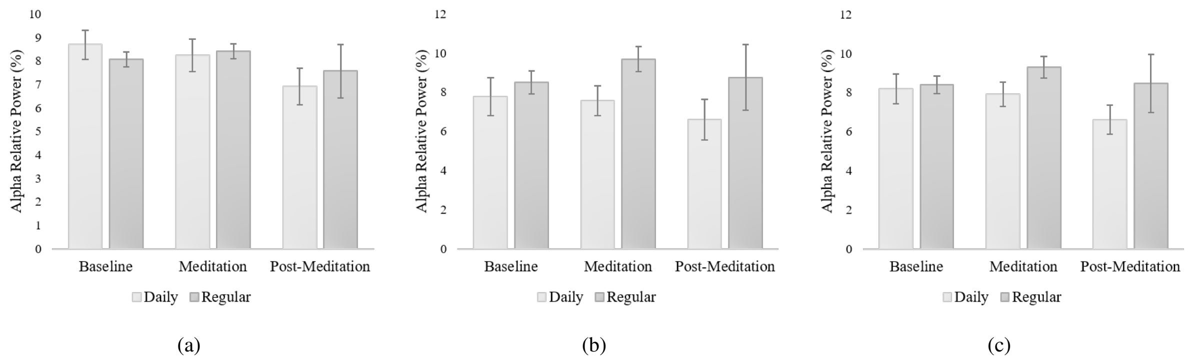
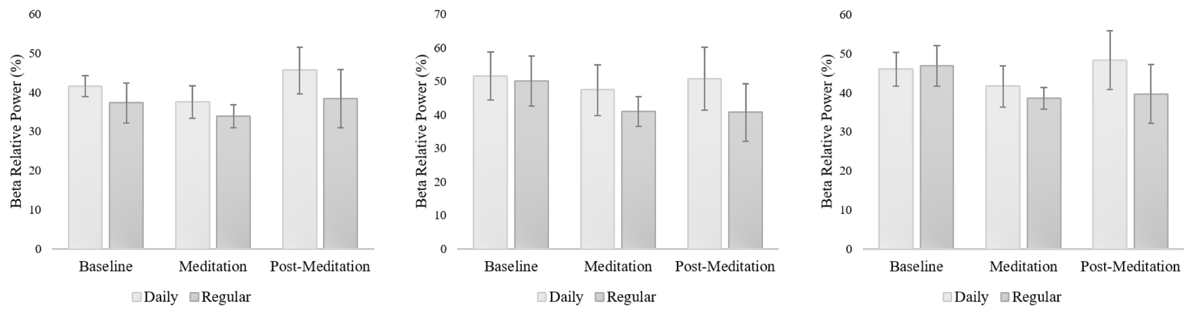


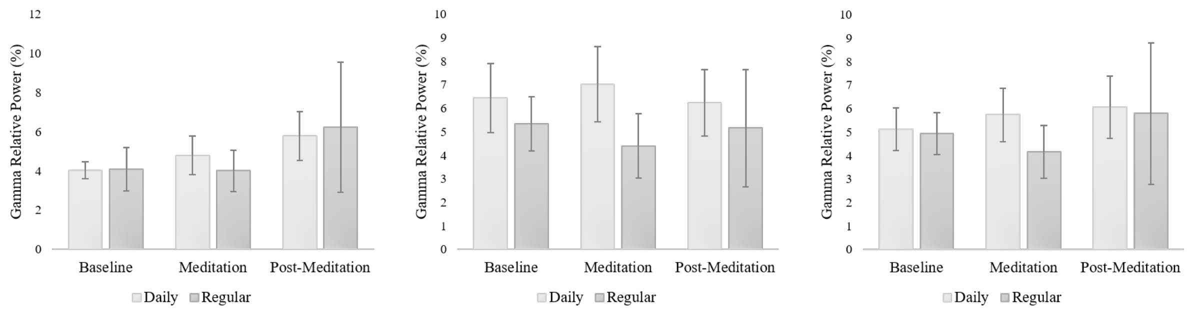
Figure B.43: Relative power of alpha band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

B. ADDITIONAL FIGURES



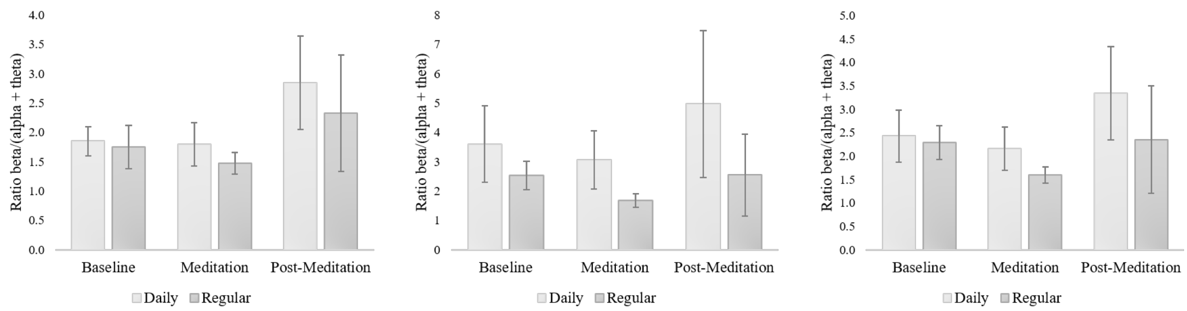
(a) (b) (c)

Figure B.44: Relative power of beta band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



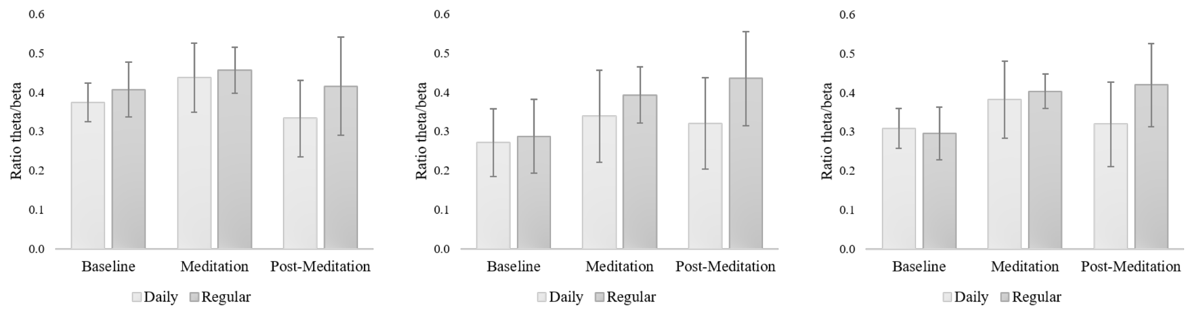
(a) (b) (c)

Figure B.45: Relative power of gamma band for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



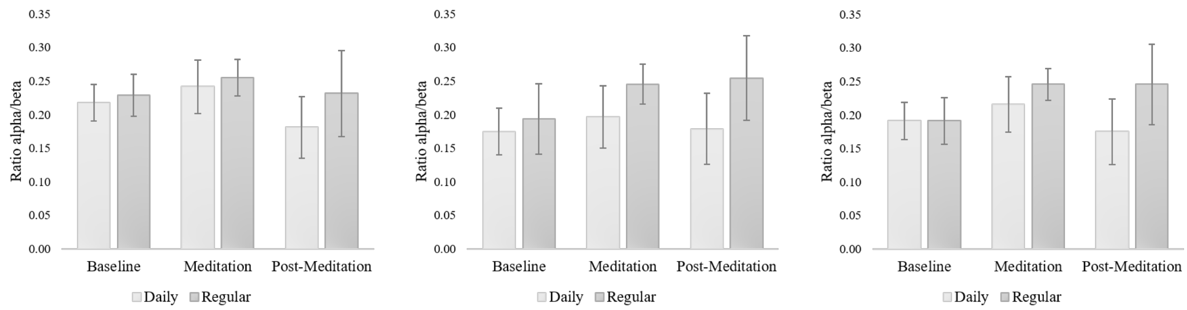
(a) (b) (c)

Figure B.46: Ratio beta/(alpha + theta) for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

Figure B.47: Ratio theta/beta for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.



(a) (b) (c)

Figure B.48: Ratio alpha/beta for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods in the (a) left, (b) right and (c) both hemispheres.

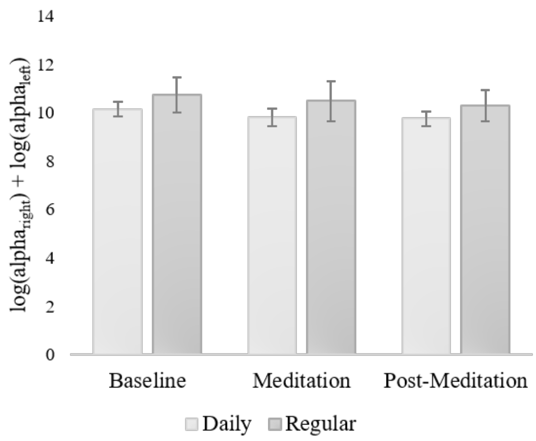


Figure B.49: Arousal for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

B. ADDITIONAL FIGURES

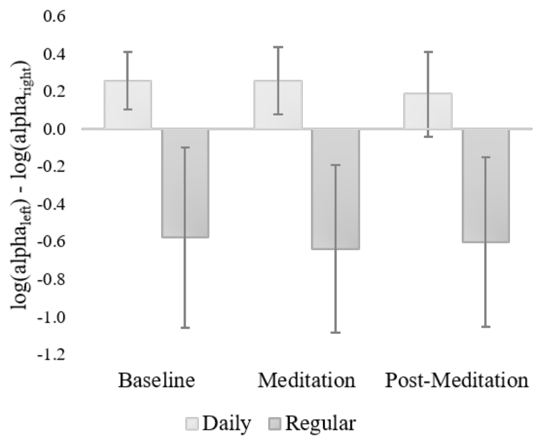


Figure B.50: Valence for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

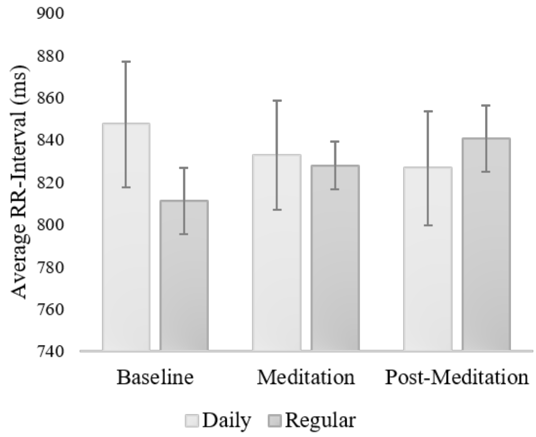


Figure B.51: Average RR-interval for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

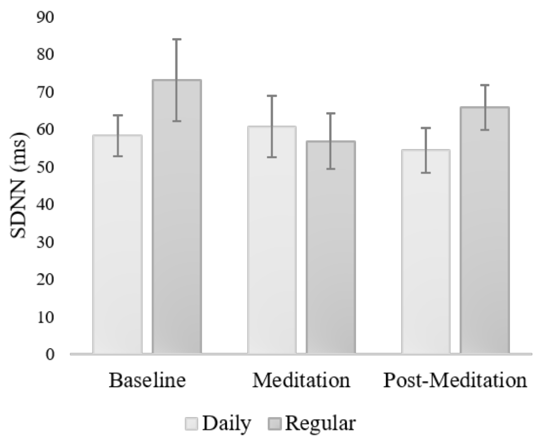


Figure B.52: SDNN for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

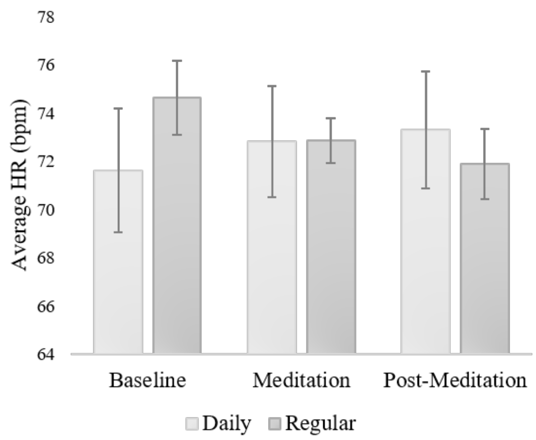


Figure B.53: Average HR for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

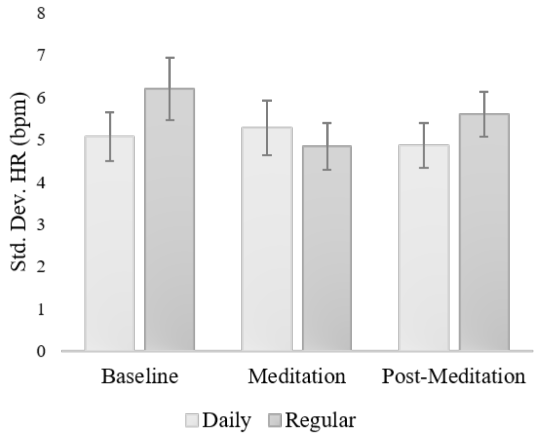


Figure B.54: Standard deviation of the HR for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

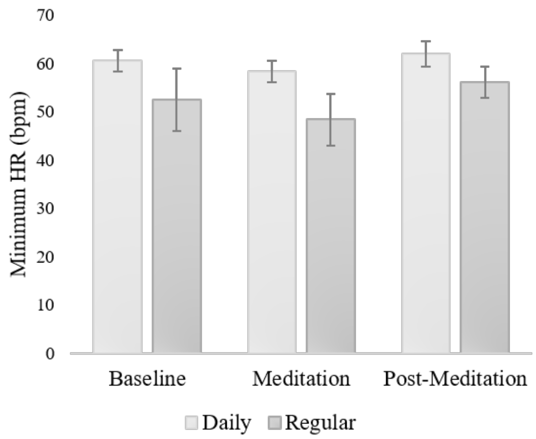


Figure B.55: Minimum HR for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

B. ADDITIONAL FIGURES

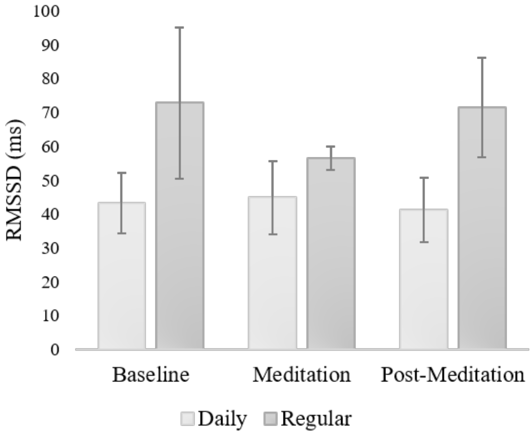


Figure B.56: RMSSD for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

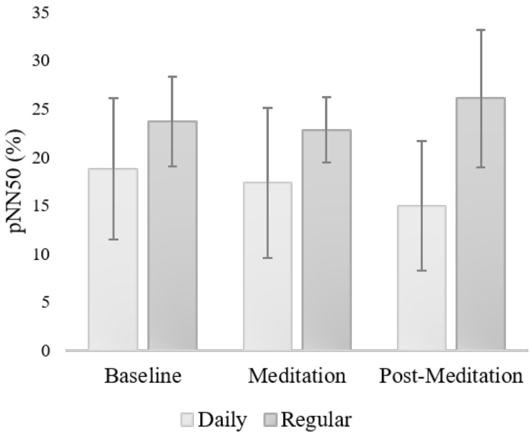


Figure B.57: pNN50 for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

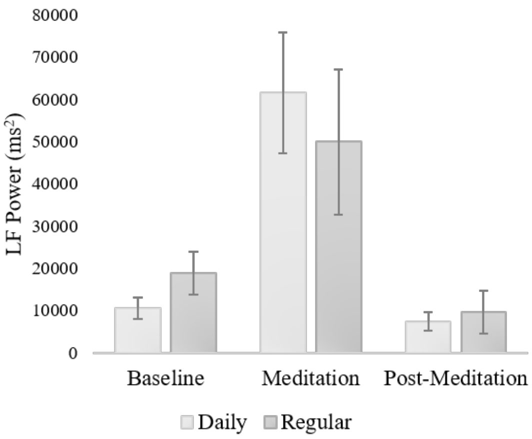


Figure B.58: LF power for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

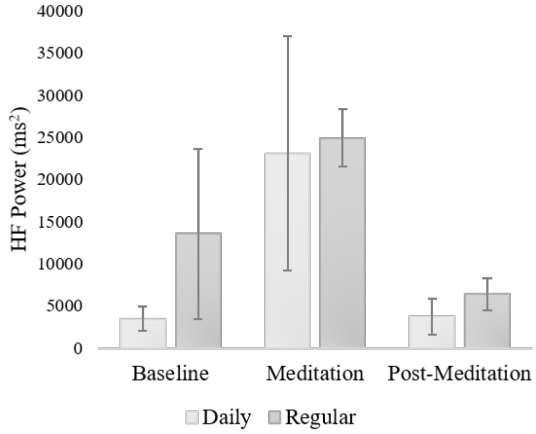


Figure B.59: HF power for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

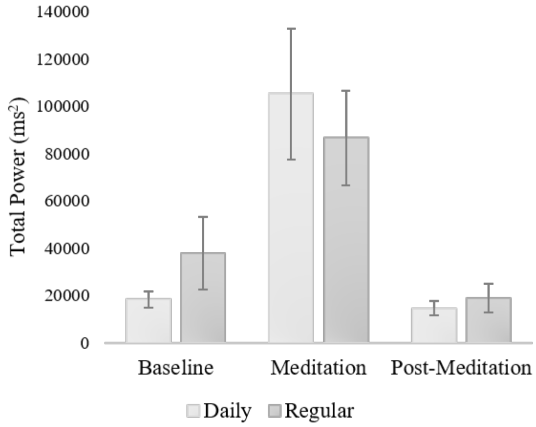


Figure B.60: Total power for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

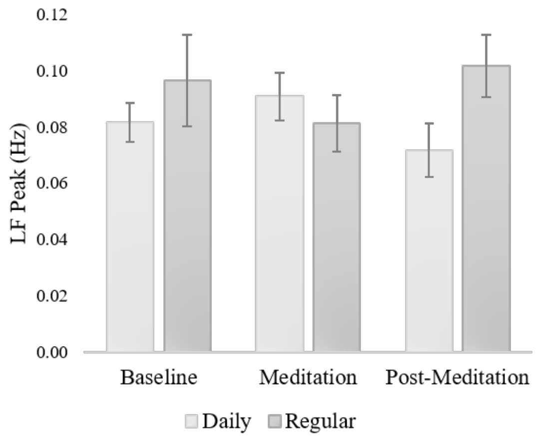


Figure B.61: LF peak for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

B. ADDITIONAL FIGURES

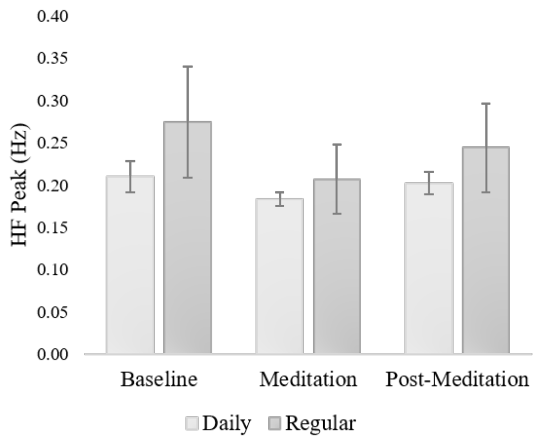


Figure B.62: HF peak for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

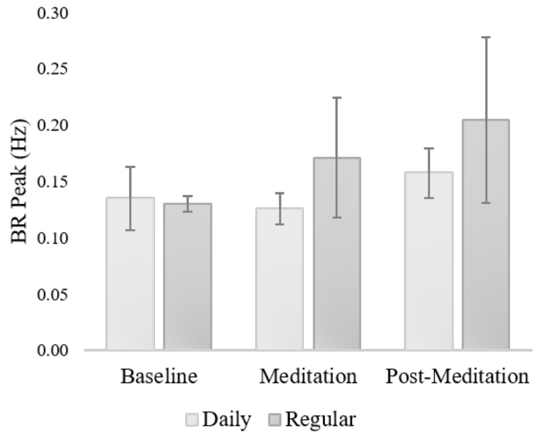


Figure B.63: Average breathing rate for the daily and regular practices of meditation during the baseline, meditation and post-meditation periods.

Appendix C

MATLAB Codes

C.1 Detection of Saturated Epochs

```
function  [bad_epoch] = remove_saturated_epoch(epoched_signal)

bad_epoch = [];
for i = 1:size(epoched_signal,2)
    idx = find(epoched_signal(:,i) > 490 | epoched_signal(:,i) < -490);
    result = strfind(diff(idx)',[1 1 1 1 1 1 1 1 1]);
    if  ~isempty(result)
        bad_epoch = [bad_epoch,i];
    end
end

end
```

C.2 Correction of OAs

```
function [corrected_signal] = correct_artefacts(signal,wave)

[c,l] = wavedec(signal,8,wave);
cD1 = wrcoef('d',c,l,wave,1);
cD2 = wrcoef('d',c,l,wave,2);
cD3 = wrcoef('d',c,l,wave,3);
cD4 = wrcoef('d',c,l,wave,4);
cD5 = wrcoef('d',c,l,wave,5);
cD6 = wrcoef('d',c,l,wave,6);
cD7 = wrcoef('d',c,l,wave,7);
cD8 = wrcoef('d',c,l,wave,8);
cA8 = wrcoef('a',c,l,wave,8);

th_cD3 = 1.5 * std(cD3);
th_cD4 = 1.5 * std(cD4);
th_cD5 = 1.5 * std(cD5);
th_cD6 = 1.5 * std(cD6);
th_cD7 = 1.5 * std(cD7);
th_cD8 = 1.5 * std(cD8);

cD3(cD3 > th_cD3 | cD3 < -th_cD3) = 0;
cD4(cD4 > th_cD4 | cD4 < -th_cD4) = 0;
cD5(cD5 > th_cD5 | cD5 < -th_cD5) = 0;
cD6(cD6 > th_cD6 | cD6 < -th_cD6) = 0;
cD7(cD7 > th_cD7 | cD7 < -th_cD7) = 0;
cD8(cD8 > th_cD8 | cD8 < -th_cD8) = 0;

corrected_signal = cD1 + cD2 + cD3 + cD4 + cD5 + cD6 + cD7 + cD8 + cA8;

end
```

C.3 Extraction of EEG Measures

```
% ARRAY CONTAINING ALL THE PARTICIPANTS FOR THE EEG STUDY
participants = {'P_LFe_1.txt','P_CUB_3.txt','P_AG_1.txt','P_SR_2.txt',...
                'P_LB_1.txt','P_SP_1.txt','P_JC_2.txt','P_JV_2.txt',...
                'P_MC_1.txt','P_AL_1.txt','P_MaD_2.txt','P_JL_1.txt',...
                'P_ME_1.txt','P_LFo_1.txt','P_TTF_1.txt','P_PTF_1.txt',...
                'P_JDF_1.txt','P_E_1.txt','P_MDD_2.txt'};

% TO SAVE THE ABSOLUTE POWER, RELATIVE POWER AND RATIOS
results_right = [];
results_left = [];
results_both = [];

% TO SAVE ASYMMETRY, AROUSAL AND VALENCE
results_other = [];

for k = 1:length(participants)

    data = importdata(string(participants(k)));
    data_ = data.data;
    data_f = data_(1:84000,:);

    fs = 100;
    N = length(data_f);
    t = linspace(0,840,N);

    eeg_right = data_f(:,7);
    eeg_left = data_f(:,6);

    eeg_right = eeg_right - mean(eeg_right);
    eeg_left = eeg_left - mean(eeg_left);

    eeg_right_epoch = buffer(eeg_right,fs);
    eeg_left_epoch = buffer(eeg_left,fs);

    % FIND COLUMN INDEX CONTAINIG THE SATURATED SEGMENTS
    bad_right = remove_saturated_epoch(eeg_right_epoch);
    bad_left = remove_saturated_epoch(eeg_left_epoch);

    % BANDPASS FILTERING
    [b,a] = butter(4,[1 40]/(fs/2),'bandpass');
    eeg_right_filtered = filtfilt(b,a,eeg_right);
    eeg_left_filtered = filtfilt(b,a,eeg_left);

    % WAVELET DENOISING TO CORRECT ARTEFACTS
    eeg_right_corrected = correct_artefacts(eeg_right_filtered,'coif3');
    eeg_left_corrected = correct_artefacts(eeg_left_filtered,'coif3');
    eeg_right_corrected_ = buffer(eeg_right_corrected,fs);
    eeg_left_corrected_ = buffer(eeg_left_corrected,fs);
    eeg_right_corrected_(:,bad_right) = 0;
    eeg_left_corrected_(:,bad_left) = 0;
```

```matlab
% RESHAPE TO COLUMN VECTOR
eeg_right_final = reshape(eeg_right_corrected_,[],1);
eeg_left_final = reshape(eeg_left_corrected_,[],1);

% LIST OF ARRAYS FROM EACH PERIOD
right = {nonzeros(eeg_right_final(1:11500)), ...
         nonzeros(eeg_right_final(13501:71500)), ...
         nonzeros(eeg_right_final(74001:84000))};

left = {nonzeros(eeg_left_final(1:11500)), ...
        nonzeros(eeg_left_final(13501:71500)), ...
        nonzeros(eeg_left_final(74001:84000))};

% EMPETY ARRAYS TO STORE THE RESULTS FROM EACH PARTICIPANT
% EEG ABSOLUTE POWER
delta_right_power = []; theta_right_power = [];
alpha_right_power = []; beta_right_power = [];
gamma_right_power = []; total_right_power = [];
delta_left_power = []; theta_left_power = [];
alpha_left_power = []; beta_left_power = [];
gamma_left_power = []; total_left_power = [];
delta_both_power = []; theta_both_power = [];
alpha_both_power = []; beta_both_power = [];
gamma_both_power = []; total_both_power = [];

% EEG RELATIVE POWER
delta_rel_right_power = []; theta_rel_right_power = [];
alpha_rel_right_power = []; beta_rel_right_power = [];
gamma_rel_right_power = []; total_rel_right_power = [];
delta_rel_left_power = []; theta_rel_left_power = [];
alpha_rel_left_power = []; beta_rel_left_power = [];
gamma_rel_left_power = []; total_rel_left_power = [];
delta_rel_both_power = []; theta_rel_both_power = [];
alpha_rel_both_power = []; beta_rel_both_power = [];
gamma_rel_both_power = []; total_rel_both_power = [];

% EEG RATIO
bat_right_ratio = []; tb_right_ratio = []; ab_right_ratio = [];
bat_left_ratio = []; tb_left_ratio = []; ab_left_ratio = [];
bat_both_ratio = []; tb_both_ratio = []; ab_both_ratio = [];

% EEG ASYMMETRY, AROUSAL AND VALENCE
asymetry = []; arousal = []; valence = [];

for p = 1:size(right,2)

    % SELECT ARRAY FROM EACH PERIOD
    eeg_right_analysis = right{p};
    eeg_left_analysis = left{p};
```

```
% RIGHT SIDE
[cwt_right,f_right] = cwt(eeg_right_analysis,'amor',fs);
delta_right = icwt(cwt_right,'amor',f_right,[1 4]);
theta_right = icwt(cwt_right,'amor',f_right,[4 8]);
alpha_right = icwt(cwt_right,'amor',f_right,[8 12]);
beta_right = icwt(cwt_right,'amor',f_right,[12 30]);
gamma_right = icwt(cwt_right,'amor',f_right,[30 max(f_right)]);

delta_right_value = (mean(delta_right.^2));
theta_right_value = (mean(theta_right.^2));
alpha_right_value = (mean(alpha_right.^2));
beta_right_value = (mean(beta_right.^2));
gamma_right_value = (mean(gamma_right.^2));
total_right_value = delta_right_value + theta_right_value + ...
    alpha_right_value + beta_right_value + gamma_right_value;

% STORE ABSOLUTE POWER, RELATIVE POWER, RATIO
delta_right_power = [delta_right_power,delta_right_value];
theta_right_power = [theta_right_power,theta_right_value];
alpha_right_power = [alpha_right_power,alpha_right_value];
beta_right_power = [beta_right_power,beta_right_value];
gamma_right_power = [gamma_right_power,gamma_right_value];
total_right_power = [total_right_power,total_right_value];
delta_rel_right_power = [delta_rel_right_power,delta_right_value/...
    total_right_value];
theta_rel_right_power = [theta_rel_right_power,theta_right_value/...
    total_right_value];
alpha_rel_right_power = [alpha_rel_right_power,alpha_right_value/...
    total_right_value];
beta_rel_right_power = [beta_rel_right_power,beta_right_value/...
    total_right_value];
gamma_rel_right_power = [gamma_rel_right_power,gamma_right_value/...
    total_right_value];
bat_right_ratio = [bat_right_ratio,beta_right_value/...
    (alpha_right_value + theta_right_value)];
tb_right_ratio = [tb_right_ratio,theta_right_value/...
    beta_right_value];
ab_right_ratio = [ab_right_ratio,alpha_right_value/...
    beta_right_value];

% LEFT SIDE
[cwt_left,f_left] = cwt(eeg_left_analysis,'amor',fs);
delta_left = icwt(cwt_left,'amor',f_left,[1 4]);
theta_left = icwt(cwt_left,'amor',f_left,[4 8]);
alpha_left = icwt(cwt_left,'amor',f_left,[8 12]);
beta_left = icwt(cwt_left,'amor',f_left,[12 30]);
gamma_left = icwt(cwt_left,'amor',f_left,[30 max(f_left)]);

delta_left_value = (mean(delta_left.^2));
```

```
theta_left_value = (mean(theta_left.^2));
alpha_left_value = (mean(alpha_left.^2));
beta_left_value = (mean(beta_left.^2));
gamma_left_value = (mean(gamma_left.^2));
total_left_value = delta_left_value + theta_left_value + ...
    alpha_left_value + beta_left_value + gamma_left_value;

% STORE ABSOLUTE POWER, RELATIVE POWER, RATIO
delta_left_power = [delta_left_power,delta_left_value];
theta_left_power = [theta_left_power,theta_left_value];
alpha_left_power = [alpha_left_power,alpha_left_value];
beta_left_power = [beta_left_power,beta_left_value];
gamma_left_power = [gamma_left_power,gamma_left_value];
total_left_power = [total_left_power,total_left_value];
delta_rel_left_power = [delta_rel_left_power,delta_left_value/...
    total_left_value];
theta_rel_left_power = [theta_rel_left_power,theta_left_value/...
    total_left_value];
alpha_rel_left_power = [alpha_rel_left_power,alpha_left_value/...
    total_left_value];
beta_rel_left_power = [beta_rel_left_power,beta_left_value/...
    total_left_value];
gamma_rel_left_power = [gamma_rel_left_power,gamma_left_value/...
    total_left_value];
bat_left_ratio = [bat_left_ratio,beta_left_value/...
    (alpha_left_value + theta_left_value)];
tb_left_ratio = [tb_left_ratio,theta_left_value/beta_left_value];
ab_left_ratio = [ab_left_ratio,alpha_left_value/beta_left_value];

% BOTH SIDES
delta_both_value = delta_right_value + delta_left_value;
theta_both_value = delta_right_value + delta_left_value;
alpha_both_value = delta_right_value + delta_left_value;
beta_both_value = delta_right_value + delta_left_value;
gamma_both_value = delta_right_value + delta_left_value;
total_both_value = delta_both_value + theta_both_value + ...
    alpha_both_value + beta_both_value + gamma_both_value;

% STORE ABSOLUTE POWER, RELATIVE POWER, RATIO
delta_both_power = [delta_both_power,delta_both_value];
theta_both_power = [theta_both_power,theta_both_value];
alpha_both_power = [alpha_both_power,alpha_both_value];
beta_both_power = [beta_both_power,beta_both_value];
gamma_both_power = [gamma_both_power,gamma_both_value];
total_both_power = [total_both_power,total_both_value];
delta_rel_both_power = [delta_rel_both_power,delta_both_value/...
    total_both_value];
theta_rel_both_power = [theta_rel_both_power,theta_both_value/...
    total_both_value];
alpha_rel_both_power = [alpha_rel_both_power,alpha_both_value/...
```

```
            total_both_value];
        beta_rel_both_power = [beta_rel_both_power,beta_both_value/...
            total_both_value];
        gamma_rel_both_power = [gamma_rel_both_power,gamma_both_value/...
            total_both_value];
        bat_both_ratio = [bat_both_ratio,beta_both_value/...
            (alpha_both_value + theta_both_value)];
        tb_both_ratio = [tb_both_ratio,theta_both_value/beta_both_value];
        ab_both_ratio = [ab_both_ratio,alpha_both_value/beta_both_value];

        % ASYMMETRY, AROUSAL AND VALENCE
        asymetry = [asymetry,log(alpha_right_value) - log(alpha_left_value)];
        arousal = [arousal,log(alpha_left_value) + log(alpha_right_value)];
        valence = [valence,log(alpha_left_value) - log(alpha_right_value)];

    end

    % STORING THE DATA FROM EACH PARTICIPANT IN ROWS
    eeg_right_table = table(delta_right_power',theta_right_power',...
                            alpha_right_power',beta_right_power',...
                            gamma_right_power',total_right_power',...
                            delta_rel_right_power',theta_rel_right_power',...
                            alpha_rel_right_power',beta_rel_right_power',...
                            gamma_rel_right_power',bat_right_ratio',...
                            tb_right_ratio',ab_right_ratio');
    results_right = [results_right;eeg_right_table];

    eeg_left_table = table(delta_left_power',theta_left_power',...
                           alpha_left_power',beta_left_power',...
                           gamma_left_power',total_left_power',...
                           delta_rel_left_power',theta_rel_left_power',...
                           alpha_rel_left_power',beta_rel_left_power',...
                           gamma_rel_left_power',bat_left_ratio',...
                           tb_left_ratio',ab_left_ratio');
    results_left = [results_left;eeg_left_table];

    eeg_both_table = table(delta_both_power',theta_both_power',...
                           alpha_both_power',beta_both_power',...
                           gamma_both_power',total_both_power',...
                           delta_rel_both_power',theta_rel_both_power',...
                           alpha_rel_both_power',beta_rel_both_power',...
                           gamma_rel_both_power',bat_both_ratio',...
                           tb_both_ratio',ab_both_ratio');
    results_both = [results_both;eeg_both_table];

    eeg_table = table(asymetry',arousal',valence');
    results_other = [results_other;eeg_table];

end
```

```
% TO EXTRACT THE BASELINE, MEDITATION AND POST-MEDITATION PERIODS
baseline_right = results_right(1:3:end,:);
meditation_right = results_right(2:3:end,:);
post_meditation_right = results_right(3:3:end,:);

baseline_left = results_left(1:3:end,:);
meditation_left = results_left(2:3:end,:);
post_meditation_left = results_left(3:3:end,:);

baseline_both = results_both(1:3:end,:);
meditation_both = results_both(2:3:end,:);
post_meditation_both = results_both(3:3:end,:);

baseline_other = results_other(1:3:end,:);
meditation_other = results_other(2:3:end,:);
post_meditation_other = results_other(3:3:end,:);
```

C.4 Extraction of PPG Measures

```
% ARRAYS CONTAINING ALL THE PARTICIPANTS FOR THE PPG STUDY
participants = {'P_LFe_1.txt','P_CUB_3.txt','P_AG_1.txt','P_SR_2.txt',...
                'P_LB_1.txt','P_SP_1.txt','P_JC_2.txt','P_JV_2.txt',...
                'P_MC_1.txt','P_AL_1.txt','P_MaD_2.txt','P_JL_1.txt',...
                'P_ME_1.txt','P_LFo_1.txt','P_TTF_1.txt','P_PTF_1.txt',...
                'P_JDF_1.txt','P_E_1.txt','P_LD_2.txt'};

% SEPARATE ANALYSIS
% participants = {'P_CUB_3.txt','P_AG_1.txt','P_SP_1.txt'};

% TO SAVE THE TIME DOMAIN AND FREQUENCY DOMAIN RESULTS
results = [];

for k = 1:length(participants)

    data = importdata(string(participants(k)));
    data_ = data.data;
    data_f = data_(1:84000,:);

    fs = 100;
    dt = 1/fs;
    N = length(data_f);
    t = linspace(0,840,N);

    ppg_signal = data_f(:,8);
    ppg_signal = ppg_signal - mean(ppg_signal);

    [b,a] = butter(5,3/(fs/2),'low');
    ppg_signal_filtered = filtfilt(b,a,ppg_signal);

    % TIME DOMAIN MEASURES
    mean_rr = []; sdnn = []; mean_hr = []; std_hr = []; min_hr = [];
    max_hr = []; rmssd = []; pnn_xx = [];

    % FREQUENCY DOMAIN MEASURES
    power_vlf = []; power_lf = []; power_hf = []; power_total = [];
    power_lf_hf = []; peak_vlf = []; peak_lf = []; peak_hf = [];
    lf_nu = []; hf_nu = []; mean_br = [];

    % SELECT THE PERIODS OF ANALYSIS - BASELINE, MEDITATION AND POST-MED
    periods = [1 11500;13501 71500;74001 84000];
    for p = 1:length(periods)

        start = periods(p,1);
        stop = periods(p,2);

        ppg_signal_analysis = ppg_signal_filtered(start:stop);

        % R-PEAK DETECTION
        [rr_peaks,rr_index] = findpeaks(ppg_signal_analysis,...
                                        'MinPeakDistance',50,...
                                        'MinPeakProminence',5);
        % [rr_peaks,rr_index] = findpeaks(ppg_signal_analysis...
        %                                 'MinPeakDistance',50);
```

```
% RR-INTERVALS/HRV
rr_interval = diff(rr_index);

% HR OVERTIME
hr = 60 * fs ./ rr_interval;

mean_rr_val = mean(rr_interval);
sdnn_val = std(rr_interval);
mean_hr_val = mean(hr);
std_hr_val = std(hr);
min_hr_val = min(hr);
max_hr_val = max(hr);
rmssd_val = sqrt(mean(diff(rr_interval).^2));
nn_xx_val = sum(abs(diff(rr_interval)) > 5);
pnn_xx_val = 100 * nn_xx_val / length(rr_interval);

% APPEND VALUES FROM EACH PERIOD
mean_rr = [mean_rr,mean_rr_val*10];
sdnn = [sdnn,sdnn_val*10];
mean_hr = [mean_hr,mean_hr_val];
std_hr = [std_hr,std_hr_val];
min_hr = [min_hr,min_hr_val];
max_hr = [max_hr,max_hr_val];
rmssd = [rmssd,rmssd_val*10];
nn_xx = [nn_xx,nn_xx_val];
pnn_xx = [pnn_xx,pnn_xx_val];

% INTERPOLATION OF THE RR-INTERVAL
fs_ = 4;
t_rr = cumsum(rr_interval);
t_rr_ = linspace(1,max(t_rr),length(t_rr)*fs_);
rr_interpolated = spline(t_rr,rr_interval,t_rr_);

% LOMB-SCARGLE PSD
[psd,freq] = plomb(rr_interpolated,fs_);

% VLF: 0.0033-0.04 Hz | LF: 0.04-0.15 Hz | HF: 0.15-0.4 Hz
vlf = psd(freq >= 0.0033 & freq < 0.04);
lf = psd(freq >= 0.04 & freq < 0.15);
hf = psd(freq >= 0.15 & freq < 0.4);

% CALCULATE POWER IN EACH BAND BY INTEGRATING THE SPECTRAL DENSITY
power_vlf_val = trapz(vlf);
power_lf_val = trapz(lf);
power_hf_val = trapz(hf);
power_total_val = power_vlf_val + power_lf_val + power_hf_val;
power_lf_hf_val = power_lf_val/power_hf_val;

% FREQUENCY WITH THE MOST POWER IN EACH BAND
peak_vlf_val = freq(psd == max(vlf));
peak_lf_val = freq(psd == max(lf));
peak_hf_val = freq(psd == max(hf));
```

```
        % FRACTION OF LF AND HF
        lf_nu_val = 100 * power_lf_val / (power_lf_val + power_hf_val);
        hf_nu_val = 100 * power_hf_val / (power_lf_val + power_hf_val);

        % BREATHING RATE
        br_val = freq(psd == max(psd(freq >= 0.1 & freq < 0.5)));

        power_vlf = [power_vlf,power_vlf_val];
        power_lf = [power_lf,power_lf_val];
        power_hf = [power_hf,power_hf_val];
        power_total = [power_total,power_total_val];
        power_lf_hf = [power_lf_hf,power_lf_hf_val];
        peak_vlf = [peak_vlf,peak_vlf_val];
        peak_lf = [peak_lf,peak_lf_val];
        peak_hf = [peak_hf,peak_hf_val];
        lf_nu = [lf_nu,lf_nu_val];
        hf_nu = [hf_nu,hf_nu_val];
        mean_br = [mean_br,br_val];

    end

    % STORING THE DATA FROM EACH PARTICIPANT IN ROWS
    ppg_table = table(mean_rr',sdnn',mean_hr',std_hr',min_hr',max_hr',...
                      rmssd',pnn_xx',power_vlf',power_lf',power_hf',...
                      power_total',power_lf_hf',peak_vlf',peak_lf',...
                      peak_hf',lf_nu',hf_nu',mean_br');

    results = [results;ppg_table];

end

% TO EXTRACT THE BASELINE, MEDITATION AND POST-MEDITATION PERIODS
baseline = results(1:3:end,:);
meditation = results(2:3:end,:);
post_meditation = results(3:3:end,:);
```