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AN INVESTIGATION OF THE IMMEDIATE EFFECTS OF MINDFULNESS MEDITATION ON MENTAL STRESS USING WEARABLE ELECTROENCEPHALOGRAPHY

Bachelor's Project Thesis

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Abstract: The omnipresence of daily stressors has a negative impact on human life. Mindfulness meditation (MM) has proven to be an effective remedy against psychological stress. This study aims to investigate the immediate neurophysiological effects of MM on mental stress. Electroencephalography (EEG) data was collected from the prefrontal cortex and temporoparietal junction of 13 adults while performing a Montreal Imaging Stress Task (MIST). Participants were randomly divided into either the test or the active control group. The participants performed one baseline MIST, one stressful MIST before, and one stressful MIST after listening to either a guided MM or an audiobook. Accuracy and stress levels as well as both α- and β-power and the β/α-ratio were computed. MM resulted in a significant decrease in stress levels, while listening to an audiobook did not. The hypotheses that α-power would increase more after MM than after the audiobook and that β-power and the β/α-ratio would decrease more after MM than after the audiobook, was not supported by any significant EEG results. Although insignificant, both α- and β-power did show more responsiveness after MM than after the audiobook, providing a promising basis for future research. Given the limitations of the current study, further investigation is needed to address the gaps.

1 Introduction

Stressful events are omnipresent in our lives and may be the root of many of today's mental and physical illnesses (Al-Shargie et al., 2016; DeLongis et al., 1988; Vaccarino & Bremner, 2024). In order to maintain our well-being, it is important to notice the presence of stress and to manage it well. Mindfulness meditation (MM) promises to help us gain control over our thoughts and feelings, leading to better stress management and resilience. So far, this effect has been researched on a behavioral level using questionnaires (Ramasubramanian, 2017; Astin, 1997; Innes et al., 2016)) and on a physiological level by looking into, for instance, blood pressure or heart-rate (Pascoe et al., 2017). One method which can provide more insights into the immediate neurophysiological effects of meditation on stress is the use of Electroencephalography (EEG). By recording electrical changes on the scalp, the current paper aims to contribute to existing literature by investigating the visibility of the stress-reducing effect of meditation in the brain.

The rest of this section delves into the motivation for this research, the state-of-the-art of EEG, MM and stress, and the scientific contributions. Lastly, I will introduce my research question and hypotheses.

1.1 Motivation

Long-term exposure to stress hormones negatively affects physical and mental well-being. It can lead to increased chances of depression (Al-Shargie et al., 2016; Lupien et al., 2009; Pascoe et al., 2020), a decrease in cognitive functioning, such as hippocampus-dependent learning and memory (Lupien et al., 1998; McEwen & Sapolsky, 1995), and a decrease in mood (Bolger et al., 1989).

Additionally, long-term daily stress can result in minor health problems, such as vulnerability to flu, sore throat, headaches, backaches (DeLongis et al.,

1988) and sleep deprivation (Åkerstedt, 2006; Utsugi et al., 2005). In worse scenarios, stress is associated with an increase risk of various life-changing illnesses, such as cardiovascular disease (Steptoe & Kivimäki, 2013; Vaccarino & Bremner, 2024) and strokes (Al-Shargie et al., 2016). Piazza et al. (2013) has shown that, in general, heightened reactivity to daily stressors increases risk of reporting a chronic physical health condition in the long-term.

The negative impact of stress is even measurable on societal levels. For instance, Hassard et al. (2018) and Pascoe et al. (2020) have reviewed that work- and academic-related stress can impose a financial burden on society in the range of hundreds of billions of dollars each year as a result of productivity losses and unsustainable employment.

An increasingly popular way to increase resilience to stress and take care of ones mental health is through the practice of MM (Dam et al., 2018). For most Westerners, MM is the most popular and approachable type of meditation. During one MM bout, one observes their thoughts as they pass through their minds without judgement or wandering off. The many benefits that follow from this include increased attention, mood and physical health (Freedman, 2004). Most importantly, it is a promising remedy against stress. MM-programs can result in small to moderate reductions of multiple negative dimensions of psychological stress, such as anxiety, depression, and pain (Goyal et al., 2014).

It is clear that stress can impair cognitive, physical and societal functioning. Importantly, it is not the exposure to daily stressors that matters, but the way one responds to it (Piazza et al., 2013). To reduce the negative impact of stress, it is essential to investigate its neurophysiological effects and how to minimize or even reverse those effects. This will provide better insights into sustainable and effective ways to deal with stress. Therefore, this thesis looks into the effectiveness of MM as a tool to minimize or reverse the neurophysiological effects of stress.

1.2 State-of-the-art

1.2.1 Electroencephalography and stress

The current paper focuses on indicating mental stress by looking at brain activity. Multiple studies have shown that acute mental stress can be observed using EEG (Al-Shargie et al., 2016; Noushad et al., 2021; Alonso et al., 2015; TuerxunWaili et al., 2020). EEG records the electrical activity in the brain resulting from the synchronized activity of thousands of neurons. The recorded brainwaves are often transformed into five main frequency bands each related to different states of mind (Table 1.1). The higher the frequencies recorded in a certain brain region, the more that region is associated with a state of active thinking.

The effect of chronic and acute stress is observable in most of these frequency bands. However, different stressors lead to different resulting patterns of brainwaves and big differences between resultant patterns of waves are found for the same type of stressors. Reviewing all literature concerning chronic and acute stressors and their effects in the brain, the most common change was observed in the α frequency, followed by changes in β and θ waves (Noushad et al., 2021). For instance, Alonso et al. (2015) utilized EEG to look at mental stress following a Stroop test. They looked specifically at high α- and high β-powers and found a decrease and increase in those bands, respectively. TuerxunWaili et al. (2020) also looked at the band powers of α and β and even included the β/α-ratio, which is computed by dividing the power of β by the power of α. They combined their EEG data with self-assessed stress levels from their participants during calmed and stressed states. As a result, they found that the β/α-ratio positively correlates with stress. This rise in β/α-ratio can be caused by an increase in β-power and/or a decrease in α-power. A study done by Al-Shargie et al. (2016) finds this same neurophysiological effect of stress. Using a Montreal Imaging Stress Task (MIST) developed by Dedovic et al. (2005), consisting of simple arithmetic equations, they induced stress on their participants while taking EEG recordings. They found that doing a stressful task like MIST increases the β-power and significantly decreases the α-power in the prefrontal cortex (PFC). Their results confirmed that α rhythm responds more significantly to mental stress than β rhythm.

Extensive research shows that there is a clear immediate response to stress visible in several frequency bands. The current paper will investigate the changes in α- and β-power and the β/α-ratio. It will do so by comparing them between three states:

Band	Frequency range	State of mind
Delta (δ)	1-4 Hz	Deep sleep
Theta (θ)	4-8 Hz	Dreaming and mind-wandering
Alpha (α)	8-12.5 Hz	Relaxed alertness
Beta (β)	12.5-30 Hz	Heightened awareness and concentration
Gamma (γ)	30-80 Hz	Heightened perception, learning and attention

Table 1.1: Frequency bands extractable from EEG recordings and their associated states of mind (Buzsaki & Draguhn, 2004; Desai et al., 2015).

a calm state (baseline), a stressed state prior to meditation (S1) and a stressed state post meditation (S2). The baseline measurement is necessary because baseline α- and β-power differ per individual when performing an arithmetic calculation task (Fernández et al., 1995). In order to measure the α- and β-power during the experiment, the Muse 2 headset is utilised (more information on Muse 2 can be found in the *Methods* section).

1.2.2 Electroencephalography and MM

MM has been shown to reduce stress and increase sense of self-control by multiple studies (Astin, 1997; Ramasubramanian, 2017; Jain et al., 2007; Innes et al., 2016; Pascoe et al., 2017; Goyal et al., 2014; Davidson et al., 2003; Antony & Prasad, 2023). However, the immediate neurophysiological effects of MM on mental stress have not previously been analyzed using EEG.

The neural changes that meditation provoke depend on many factors. Different kinds and duration of meditation lead to different results. Some studies have found that EEG power in certain frequency bands are affected by meditation. However, results on the specific frequency bands and the direction of change are not unanimous (Cahn & Polich, 2006). Kora et al. (2021) have investigated the effects of eight different meditation styles on brainwaves. Changes in α, β, and θ brainwaves were most commonly observed. Ahani et al. (2014) specifically looked at the EEG effect of MM in novice meditators and observed an increase in α-, β- and θ-power during a state of meditation. An increase in frontal midline θ-power was also observed by Takahashi et al. (2005). According to Lomas et al. (2015), MM leads to enhanced α- and θ-power while other frequency bands are unresponsive. However, Lutz et al. (2007) state that α or θ activity cannot be seen as the main marker of MM and various data points to involvement of synchronized γ activity (Lutz et al., 2007). However, this effect is mostly observed in experienced meditators and during intense concentration of attention.

1.3 Contributions

There is little research on the combined effects of meditation and stress on brainwaves. The current paper aims to contribute to the literature by looking at the neurophysiological response to MM of a brain that is already put under stress. Filling this gap will provide insights into the effectiveness of MM as a reducer of mental stress on a more detailed level. This will be done through answering the following question: What are the neurophysiological effects of one MM bout on mental stress induced by a stressful mental arithmetic task?

To answer this question, an EEG experiment will be conducted in which participants complete the MIST three times (baseline, S1 and S2). EEG will be recorded during each MIST. Between S1 and S2, the test group will follow a stress-relieving MM, while the control group will listen to an audiobook of approximately equal length.

Based on the literature, I hypothesize that average α-power will decrease from baseline to S1 for both the test and control group. From S1 to S2, α-power is hypothesized to increase more after meditating than after listening to an audiobook. Additionally, I expect β-power to increase when comparing baseline to S1 for both the test and control group. A decrease in β-power is expected when comparing S1 to S2. This decrease is hypothesized to be larger for the test group than for the control group. Lastly, β/α-ratio is expected to increase from baseline to S1 and decrease from S1 to S2. Again, this decrease is hypothesized to be larger for the test group than for the control group.

2 Methods

To investigate α and β brainwaves, the current paper has conducted a pre-post-design within- and between-subjects study. Participants were randomly assigned to either the test or control group. Both groups performed one calm MIST (baseline) and two stressful MISTs - one pre meditation/audiobook (S1) and one post meditation/audiobook (S2). EEG data was collected during the entire experiment.

The experiment design is based on the aforementioned MIST as executed by Al-Shargie et al. (2016). During a MIST, participants need to solve mental arithmetic equations consisting of three numbers. Equations contained only three one-digit integers (ranging from 1 to 9) and operators were limited to subtraction ('-') and addition ('+'), e.g. "$2 + 4 - 5 =$ ". Each MIST contains five active blocks of 30 seconds and five rest blocks lasting for 20 seconds. Thus, the total duration per MIST is four minutes and 10 seconds. During the active blocks, equations were presented to the participants. Participants could put in their answer by pressing a number on the keyboard. All answers were one-digit integers ranging from 0 to 9. During the rest blocks, a fixation dot appeared on the screen for the participants to focus on. A count down from 3 to 1 indicated the start of the next active block. Figure 2.1 displays the set up of the screen during each MIST.

The baseline MIST can be seen as a practice round for the participants and was used to estimate average response time for each individual. During this task, participants were instructed to solve the equations as quickly and accurately as possible, but they could take as long as they needed to solve the equations. Their response time per equations was recorded and averaged over all five blocks. They did not receive any feedback on their performance. During this task, participants were intended to feel calm.

S1 and S2 were identical to each other. Contrary to the baseline, participants were put under stress by adding various stressors to the task. First of all, a time limit was set equal to their average response time during the baseline reduced by 10%, to induce stress through time pressure. Secondly, negative feedback was displayed on the answer bar when a participant put in an incorrect answers, i.e. "Wrong answer!", or exceeded the time limit, i.e. "Too late!". Thirdly, participants' accuracy was displayed alongside the average peer performance. Based on the original MIST experiment, participants were expected to answer 40% to 50% of the equations correctly and on time when setting a time limit equal to 90% of their baseline average response time (Dedovic et al., 2005). The thought of performing significantly worse than peers is supposed to induce additional stress on the participants. Therefore, average peer performance was fabricated to be 84%. Lastly, the current thesis extended the MIST design of Al-Shargie et al. (2016) by inducing additional stress using a monetary reward dependent on their performance. During S1 and S2, participants' reward was displayed alongside their accuracy. The initial reward for S1 was set to €7. Each incorrect answer resulted in a five cent decrease of the reward while each correct answer increased the reward by five cent. Participants were told they could receive a maximum reward of €8. The initial reward for S2 was set to the final reward of S1. During the rest period, the reward and accuracy bars were kept on the screen alongside the fixation dot to create more awareness and stress.

2.1 Experimental task

2.2 Experiment procedure

The outline of the experiment can be found in Figure 2.2. Each participant read and signed a consent form which included an overview of the procedure. They were given the opportunity to ask any question at any point during the experiment.

After careful instruction, participants completed baseline and S1 consecutively. This was followed by either 12 minutes of MM or 12 minutes of audiobook. These audio tasks are more clearly specified in the following subsections. Participants had to fill out a post-listening comprehension assessment or meditation engagement assessment to ensure they payed attention to the audio task. Lastly, participants performed S2. Immediately following S1 and S2, participants had to indicate the level of stress they had experienced while performing the task on a scale of 1 to 5, with 1 being not stressful at all and 5 being very stressful.

The total experiment, including set up and ques-

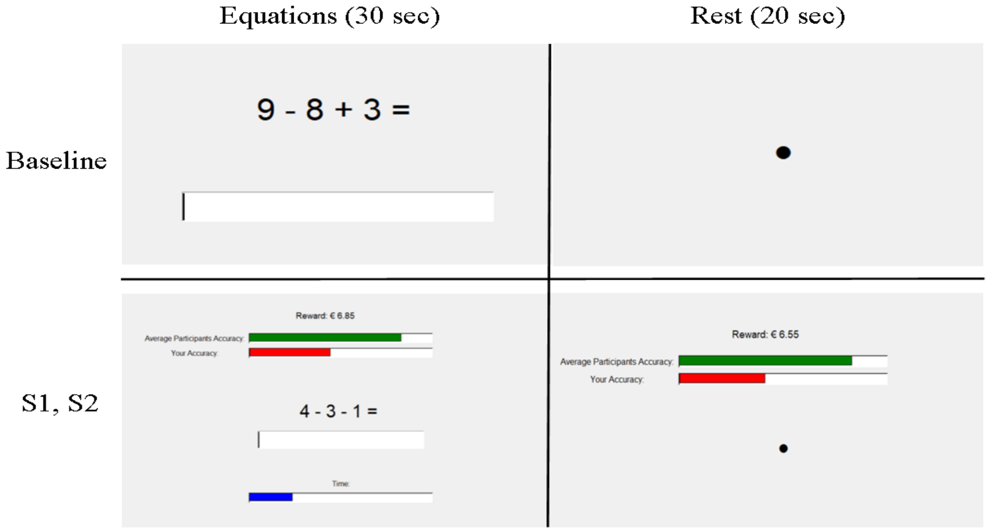

Figure 2.1: MIST blocks. Baseline, S1 and S2 each consist of five blocks of 30 seconds equations and five blocks of 20 seconds rest. After 17 seconds rest, a countdown from 3 to 1 is presented on the place of the fixation dot to indicate the start of next block of equations. After the fifth block of rest, participants were shown a new screen providing further instructions.

tionnaires, lasted about 30 to 40 minutes. Accuracy as well as the self-evaluated stress level of each participant during each MIST was evaluated as a scoring metric. EEG measurements were recorded during the whole experiment.

2.2.1 Meditation condition

In between S1 and S2, the test group listened to a guided MM. The chosen meditation was called *Taking In The Good* obtained from the mobile application Smiling Mind. Smiling Mind (`https://www.smilingmind.com.au/`) is an Australian organization addressing the mental problems amongst its citizens by providing a free app consisting of many different meditation programs. Its effectiveness has been proven by multiple studies which found Smiling Mind to have a positive impact on the mental health of adults (Flett et al., 2019; Mani et al., 2015; Rodrigues, 2022). Rodrigues (2022) has investigated the effectiveness of using Smiling Mind to reduce work-related stress using pre- and post-intervention questionnaires. Participants reported improvement of their mental health and consequently feeling less stressed at work.

The meditation *Taking In The Good* has a duration of 12 minutes and 12 seconds. It is based on the work of Dr. Rick Hanson, who has done a lot of research on the neuroscience behind meditation (Hanson, 2009). This practice is part of a mindfulness meditation program called Stress Management. During the meditation, the goal is the counteract the negativity bias of the brain which makes humans more susceptible to absorb negative experiences than positive experiences. Through this practice, participants make a conscious effect to notice the good in their lives, creating a more balanced perspective and building resilience. Stronger resilience in turn reduces stress (Montpetit et al., 2010; Russo et al., 2012; Southwick & Charney, 2012). After the MM bout, participants completed an engagement assessment to ensure they participated as desired. This assessment is further described in the *Measures* subsection.

2.2.2 Control condition

The control group was asked to listen to an audiobook playing the first chapter of "The Hobbit" by J.R.R. Tolkien. The recording lasted for 11 minutes and 43 seconds. Reading or listening has been used as an active control group activity by a multitude of comparable studies (Eisenbeck et al. (2018); Kramer et al. (2013); Zeidan et al. (2010); Robe &

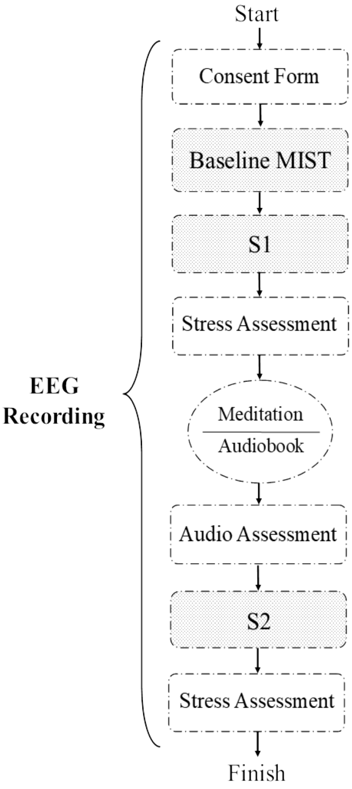

Figure 2.2: Experimental procedure.

Dobrean (2023); Pontifex et al. (2019)). Additionally, doing an audio task requires a similar amount of attention and concentration as a meditation task (Eisenbeck et al. (2018)). Participants had to complete a post-listening comprehension assessment, which is described further in the *Measures* subsection.

2.3 Participants

Participants were recruited by making use of the Artificial Intelligence mailing list at the University of Groningen and word-to-mouth. In total 18 participants completed the experiment. All of them were novice meditators. Due to technical difficulties of the EEG recording equipment during data collection, 13 participants have been included in the study. Participants had the opportunity to view their own EEG data and task scores. Additionally, all participants received a financial reimbursement of €8 for their participation, even though they were told their reward would be based on their performance. Participants were randomly divided into either the meditation or control group. The control group (n=6) had an average age of 21.2 years (SD = 1.5). 66.7% was male and 33.3% female. The meditation group (n=7) had an average age of 26.4 years (SD = 13.7). 75% was male and 25% female. All relevant demographics per participant can be found in Appendix A.

2.4 Measures

During the MISTs, the participants' reaction time, total number of correct answers, and total number of answered equations were recorded. After completing the audio task in the form of either an audiobook or a guided meditation, participants received a comprehension/engagement assessment in the form of a multiple choice questionnaire (see Appendix B). This post-listening comprehension/engagement assessment was done to measure the degree of attention paid to the listening task. Participants who showed little to no comprehension of the task, would be excluded from the experiment. This did not apply to any of the 18 initial participants.

2.5 EEG recordings

EEG data were recorded with the Muse 2 headset (InteraXon Inc., Ontario, Canada). The Muse headset is a consumer-grade EEG device specifically developed for measuring and tracking one's meditation sessions. Studies have shown its potential as a research tool to effectively record EEG signals (Surangsrirat & Intarapanich, 2015; Li et al., 2015; Krigolson et al., 2017; Suhaimi et al., 2018; Bosworth, 2019; Krigolson et al., 2021; Lazarou et al., 2023). The headset is placed across the forehead and behind the ears. It utilises four dry sensors, two near the PFC and two near the temporoparietal junction (TPJ). These four sensors correspond to the four channel electrodes complying with the 10/20 system: AF7 (left PFC), AF8 (right PFC), TP9 (left TPJ), TP10 (right TPJ) (see Figure 2.3). Data were sampled at 255 Hz and referenced to the FPz channel.

The choice for the Muse 2 headset as recording equipment follows from its user-friendly design. Utilizing Muse is a more cost and time efficient way

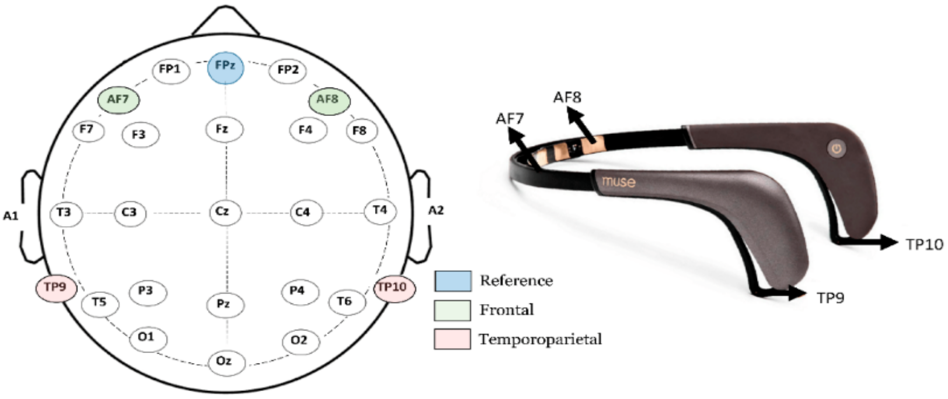

Figure 2.3: Muse headset (Tripathi & Sharma, 2023). Left: sensor placement on the head and corresponding brain regions included in the brainwave recordings. Right: physical device that is placed on the forehead and behind the ears of its user.

to take EEG measurements as it features only dry electrodes, discarding time-consuming setups using gel or saline (Sawangjai et al., 2019). Moreover, InterAxon automatically detects and accounts for artifacts such as eye blinks and jaw clenches.

The Muse headset was connected using the BlueMuse application (`https://github.com/kowalej/BlueMuse`) and synced with the experiment through Lab Streaming Layer (LSL) (`https://github.com/sccn/labstreaminglayer`). Through LSL, the recordings were saved in XDF files on the desktop.

2.5.1 Data Processing

The data processing was performed using python's MNE library (Gramfort et al., 2013). First, the raw EEG data consisting of the four electrode channels AF7, AF8, TP9, and TP10 of each participant was aligned with the corresponding experimental triggers. For two participants, essential triggers were missing from the data which led to exclusion of those participants from the analysis.

Second, the raw EEG data were filtered. A Notch filter at 50 Hz was applied to reduce power line noise. Additionally, based on Al-Shargie et al. (2016), a 30 Hz low-pas filter and a 1 Hz high-pass filter were applied to disregard the data which were not of interest.

Subsequently, from the filtered data the 30-second intervals during which participants were solving equations, were extracted. As a result, 15 30-second intervals were obtained for each participant: five for the baseline, five for S1 and five for S2. S2 was missing for one participant in the meditation group and for one participant in the audiobook group. These participants were still kept for the analysis. Over each MIST, The power spectral density (PSD) was computed for each channel of each participant using Welch's method (Welch, 1967) to visually inspect the quality of their signals. After visual inspection of each channel, bad channels were removed from the analysis. AF7 was removed for six participants. AF8 and TP10 were both removed once. One participant was excluded entirely because of noisy data. The bad channels were most likely the result of insufficient skin contact between the Muse headset and the scalp.

For each participant, the spectrum was retrieved from their PSD and the log of this spectrum was computed to obtain the absolute band powers. The mean, minimum, maximum and medium power were computed over the frequency ranges of α and β. This was done separately for the baseline, S1 and S2. For each MIST, mean, minimum, maximum and medium power was analysed in all channels individually and for all relevant combinations of channels, being PFC = AF7 + AF8, TPJ = TP9 + TP10 and all = AF7 + AF8 + TP9 + TP10. This was done to analyse differences between brain regions and the two hemispheres. Furthermore, based on the approach of TuerxunWaili et al. (2020), the mean, minimum, maximum and medium band powers of the β/α-ratio were computed for all individual and combined channels. After visual inspection of these values, average band power was chosen as most reliable and informative measure to compare brain activity between MISTs. Additionally, the combinations of channels were more informative than the separate channels. Therefore, the statistical tests were performed on the average band powers in those combinations of channels.

Lastly, the participants' accuracy during the baseline, S1 and S2 was calculated by as follows:

$$\frac{N_{correctAnswers}}{N_{equationsAnswered}} * 100\%$$

Additionally, participants' performance on the listening assessment was evaluated. One participant has been excluded based on poor involvement with the audiobook (28.57% accuracy on the assessment) and one participant has been excluded after not finishing the entire MM.

3 Results

During the MISTs, accuracy, self-assessed stress-levels and the EEG band powers of α and β were recorded for both the meditation and control group. From these measures, average α- and β-power and average β/α-ratio in the PFC and TPJ were calculated per MIST. These variables will help give insights into the immediate effects of one MM bout on stress in the brain. In this section, the results of the statistical tests on these variables are reported.

3.1 Assumptions

Before delving into statistical analyses, independence of observations is assumed. Each participant was independently tested and is assumed not to affect the outcome of another participant. Additionally, the small sample size ($N_{meditation} = 8$, $N_{control} = 6$) required a look into the distribution of the data to determine which statistical tests were appropriate. Normality and variance of the data were assessed for accuracy and self-assessed stress levels as well as for the α- and β-power and the β/α-ratio. Normality was assessed using a Shapiro-Wilk test (Shapiro & Wilk, 1965). Variance between the meditation and control group was assessed using a Levene test (Levene, 1960). As per default, the median was used as center and the data was not trimmed. For all statistical tests the significance level was set to 0.05.

3.1.1 Accuracy

Based on Shapiro's tests, the distribution of accuracy during baseline significantly deviated from normal (W = 0.80, p = .04) for the meditation group. Both the distribution of accuracy in S1 (W = 0.85, p = .12) and S2 (W = 0.83, p = .07) did not significantly deviate from normal in this group. For the control group, the distribution of accuracy during baseline (W = .82, p = .09), S1 (W = 0.93, p = .59) and S2 (W = 0.90, p = .37) did not significantly deviate from normal.

Tests of equal variance showed no significantly different variance in accuracy during baseline (F(1,12) = 0.88, p = .37), S1 (F(1,12) = 0.90, p = .36) and S2 (F(1,12) = 1.23, p = .29) between the meditation and control group.

3.1.2 Self-assessed stress levels

Based on Shapiro's test, the distribution of self-assessed stress levels after S1 (W = 0.66, p = .001) and S2 (W = 0.77, p = .02) did significantly deviate from normal in the meditation group. In the control group, the distribution of self-assessed stress levels in S1 (W = 0.50, p = 2.07) and S2 (W = 0.91, p = .42) did not significantly deviate from normal.

Levene tests showed that the variance of stress levels for S1 (F(1,12) = 0.96, p = .35) and S2 (F(1,12) = 1.25, p = .29) did not significantly differ between the meditation and control group.

3.1.3 EEG data

Normality of the average α and β bands and the β/α-ratio during baseline, S1 and S2 were assessed for meditation and control. This was done separately for the PFC and TPJ electrodes as well as for all electrodes together. For the meditation group, the distribution of average α-power measured in the PFC during baseline (W = .81, p = .04) and average α-power in [AF7, AF8, TP9, TP10] during S1 (W = .65, p = .001) showed to significantly deviate from normal. Average β-power measured by the TPJ electrodes during baseline showed to be significantly different from normal (W = .81, p = .04). Also, for the control group, the average β/α-ratio

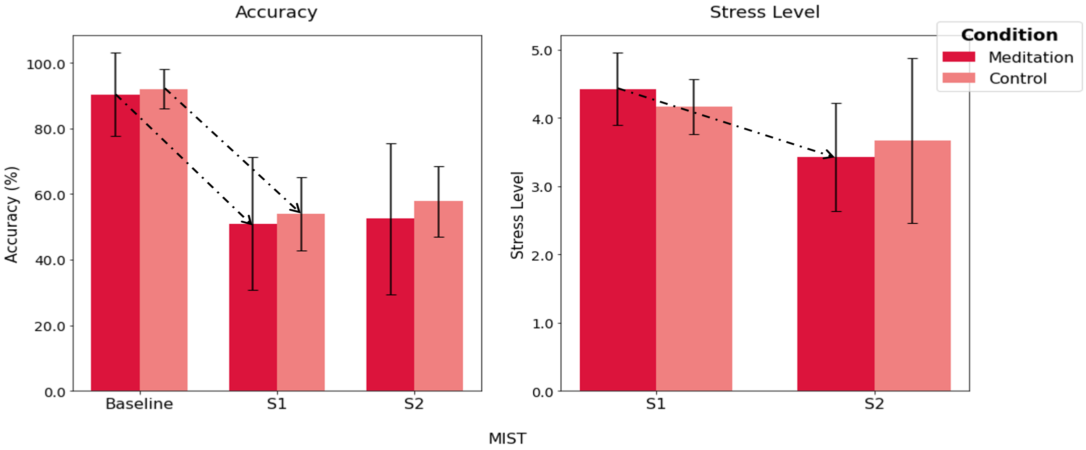

Figure 3.1: Accuracy and stress levels averaged over all participants in the meditation and control group with SD error bars. Dotted lines highlight significant results.

measured by the PFC electrodes during S1 showed to be significantly different from normal (W = .61, p < .001). All other tests did not reject normality.

Variance of the EEG data between the meditation and control group was assessed for average α and β bands and average β/α-ratio in baseline, S1 and S2 for the PFC, TPJ and all electrodes together. All tests showed no significant differences in variance between the meditation and control group. As such, the homogeneity of variance assumption is met.

3.2 Findings

All statistical tests were performed using the SciPy (SciPy 1.7.3) stats library in Python (Python 3.9.12). One-tailed independent t-tests (Wilcoxon, 1992) were applied to compare accuracy and self-assessed stress levels within groups. One-tailed Wilcoxon signed rank tests were used as a non-parametric analog. A decrease in accuracy was predicted when comparing baseline to S1 for both groups. Accuracy in S1 and S2 was compared using a two-tailed t-test for both groups. For self-assessed stress levels, one-tailed t-tests tested a decrease going from S1 to S2 for both groups.

Spearman's rank correlation test (Spearman, 1904) was performed on the meditation group to calculate correlations between accuracy and self-assessed stress levels and Pearson's correlation test (Pearson, 1895) was performed on the control group.

Lastly, for the EEG data, one-tailed independent t-tests were performed to test within-group comparisons. Wilcoxon signed rank tests were used on the non-parametric data. One-tailed paired t-tests and the non-parametric Mann-Whitney-u tests (Mann & Whitney, 1947) have been performed to compare differences in power bands between the two groups. For all statistical tests the significance level was set to 0.05.

3.2.1 Listening Assessments

Participants in the control group completed their listening comprehension assessments with a mean accuracy of $\bar{x}$ = 62.29% (SD = 21.60%). Participants in the meditation group showed a mean score of $\bar{x} = 4.23$ out of 5 (SD = 0.7) on their self-assessed levels of participation in the meditation. The statistics per question of both assessments can be found in Appendix B.

3.2.2 Accuracy

Participants in the meditation condition achieved a significantly higher average accuracy (M = 90.37%, SD = 12.80%) during baseline than during S1 (M = 51.01%, SD = 20.33%), W = 28.0, p < .001. The difference in accuracy between S1 and S2 (M = 52.53%, SD = 23.05%) was not significant in any direction (t(6) = 0.13, p = .90).

Additionally, participants in the control group achieved a significantly higher average accuracy (M = 91.98%, SD = 6.03%) during baseline then during S1 (M = 53.90%, SD = 11.16%), t(4) = 7.35, p = .02. The difference between S1 and S2 (M = 57.78%, SD = 10.81%) was not significant in any direction (t(4) = -0.61, p = .55) (see Figure 3.1).

3.2.3 Self-assessed stress levels

In the meditation group, the average self-assessed stress level before the MM bout (M = 4.43, SD = 0.53) was found to be significantly higher than the self-assessed stress level after the MM (M = 3.43, SD = 0.79) based on Wilcoxon's test (W = 21.0, p = .01). Contrarily, the control group showed no significant difference between the average self-assessed stress level before (M = 4.17, SD = 0.41) and after (M = 3.67, SD = 1.21)) the audiobook based on a one-sided independent t-test (t(4) = 0.96, p = .18) (see Figure 3.1).

3.2.4 Correlation between accuracy and stress levels

To investigate the relationship between participants' self-assessed stress levels and their accuracy during S1 and S2, a Spearman's rank correlation test was conducted for the meditation group. This was due to the non-normal distribution of the data in this group. A Pearson's correlation test was conducted for the control group. For the meditation group, there was a significant negative correlation found between self-assessed stress levels and accuracy during S1 ($r_s(6)$ = -0.87, p = .01). A moderate negative correlation between stress levels and accuracy was also found for S2 ($r_s(6)$ = -0.41, p = .35). For the control group, moderate yet insignificant correlations were found for S1 ($r_p(4)$ = -0.29, p = .58) and S2 ($r_p(4)$ = -0.63, p = .18). Although insignificant, the negative correlation between self-assessed stress and accuracy is visible for both groups in Figure 3.2.

3.2.5 EEG data

One-tailed paired t-tests were performed on within-group comparisons of average α- and β-power in the PFC, TPJ and both regions between baseline, S1 and S2. The average powers of each band averaged over all electrodes can be viewed per MIST in Figure 3.3. The split view differences for the PFC and TPJ electrodes can be found in Appendix C.

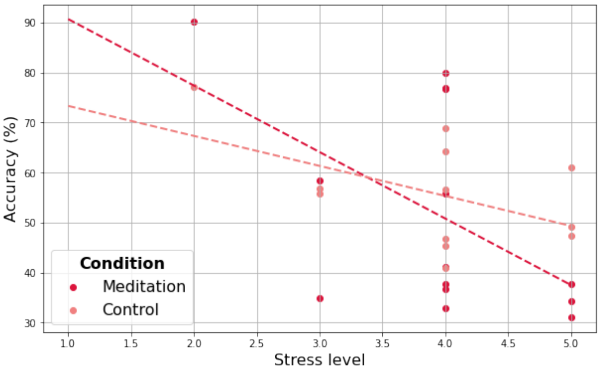

Figure 3.2: Correlation between self-assessed stress levels and accuracy for participants in the meditation and control group averaged over S1 and S2.

One-tailed Wilcoxon signed rank tests were performed on all data that did not met normality and variance assumptions which included baseline-α in the PFC, baseline-α in the TPJ, and S1-α in all electrodes together.

The average β/α-ratio was tested using an one-tailed independent t-test or, in case the data failed to meet the normality and variance assumptions, an one-tailed Mann-Whitney-U test. Independent tests were necessary as the number of data points for the β/α-ratio differed per MIST.

In the meditation group, the decrease of β-power from S1 (M = -1.15, SD = 3.54) to S2 (M = -1.74, SD = 1.98) was found to be significant for the PFC (t(6) = 2.46, p = .01). The decrease of β-power at the TPJ from S1 (M = 3.69, SD = 1.44) to S2 (M = 2.36, SD = 1.55) was also found to be significant (t(6) = 3.29, p = .01). The same applies to the decrease from S1 (M = 1.44, SD = 2.19) to S2 (M = 0.53, SD = 1.09) when looking at both regions combined (t(6) = 3.53, p = .008).

For the control group, the average β-power significantly increased from baseline (M = -1.54, SD = 2.35) to S1 (M = 0.09, SD = 2.12) in the PFC (t(4) = -3.87, p = .006). The increase from baseline (M = 2.74, SD = 1.06) to S1 (M = 3.80, SD = 1.72) at the TPJ was also significant (t(4) = -1.77, p = .03). The same applies to the increase from base-

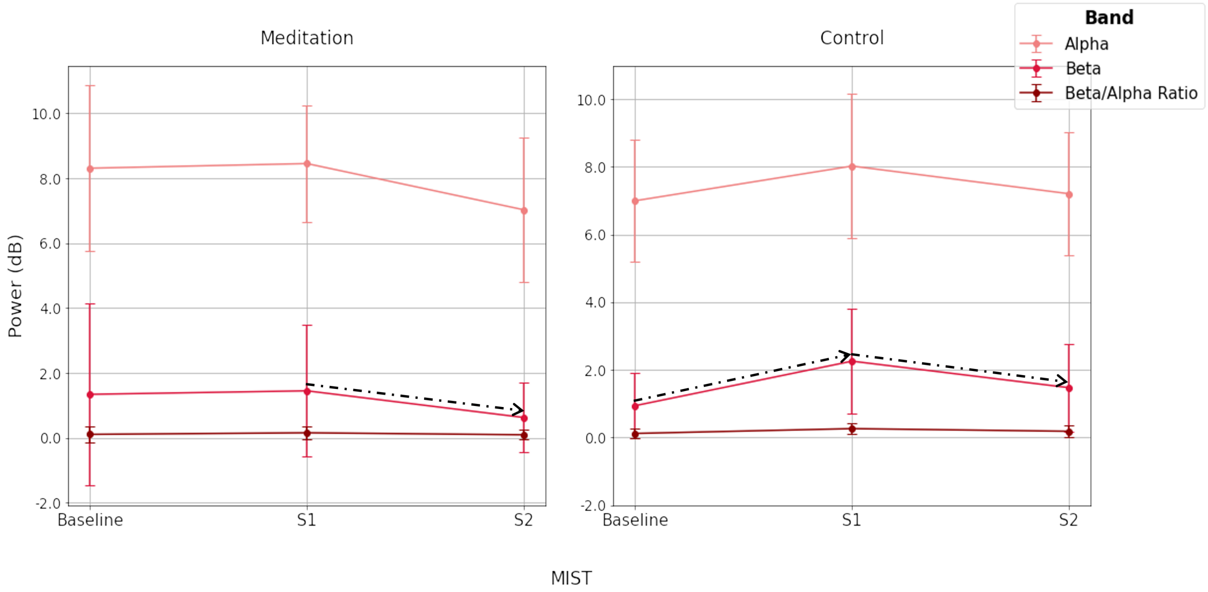

Figure 3.3: Differences in α-, β- and β/α-power in baseline-S1 (left) and S1-S2 (right) with SD error bars. Dotted lines highlight significant results.

line (M = 0.94, SD = 1.05) to S1 (M = 2.25, SD = 1.70) when looking at both regions combined (t(4) = -4.63, p = .003). The decrease of β-power from S1 to S2 (M = 2.42, SD = 1.98) was found to be significant at the TPJ (t(4) = 1.89, p = .03). Furthermore, β-power significantly decreased from S1 to S2 (M = 1.22, SD = 1.43) in both regions combined (t(4) = 1.74, p = .04). All other statistical tests did not show any significance. The split view differences for the PFC and TPJ electrodes can be found in Appendix C. All p-values for the within-group comparisons can be found in Table 3.1.

Between group comparisons were made by calculating the differences of α-, β- and β/α-power between baseline-S1 and S1-S2 for both groups over the PFC, TPJ and all electrodes (see Figure 3.4). Two-tailed independent t-tests, in combination with the non-parametric Mann-Whitney-U test, were performed on this data.

The change in α in the PFC from S1 to S2 was significantly different between meditation and control (t(12) = -2.03, p = .04). Also, the change in β in the frontal electrodes from baseline to S1 was significantly different between meditation and control (t(12) = -1.93, p = .03). All other statistical tests did not show any significance. The split view differences for the PFC and TPJ electrodes can be found in Appendix C. All p-values for the between-group comparisons can be found in Table 3.2.

Based on these results, the null-hypotheses, stating that α-, β- and β/α-power do not change when experiencing stress and that there is no significant difference in α-, β- and β/α-power between the meditation and control group when comparing pre and post listening, could not be rejected.

4 Discussion

The current study aimed to provide insights into the immediate neurophysiological effects of MM on mental stress. Mental stress was induced on participants using several MISTs. In between two stressful tasks (S1 and S2) participants listened to either a guided MM (test) or an audiobook fragment (control). EEG measurements were taken during the whole recording and split into three useful batches. EEG recordings were analysed separately for the baseline, S1 and S2. From baseline to S1, average α-power was hypothesized to decrease while average β-power and β/α-ratio was hypothesized to increase. MM was hypothesized to reverse this effect of stress in the brain more than listening to an au-

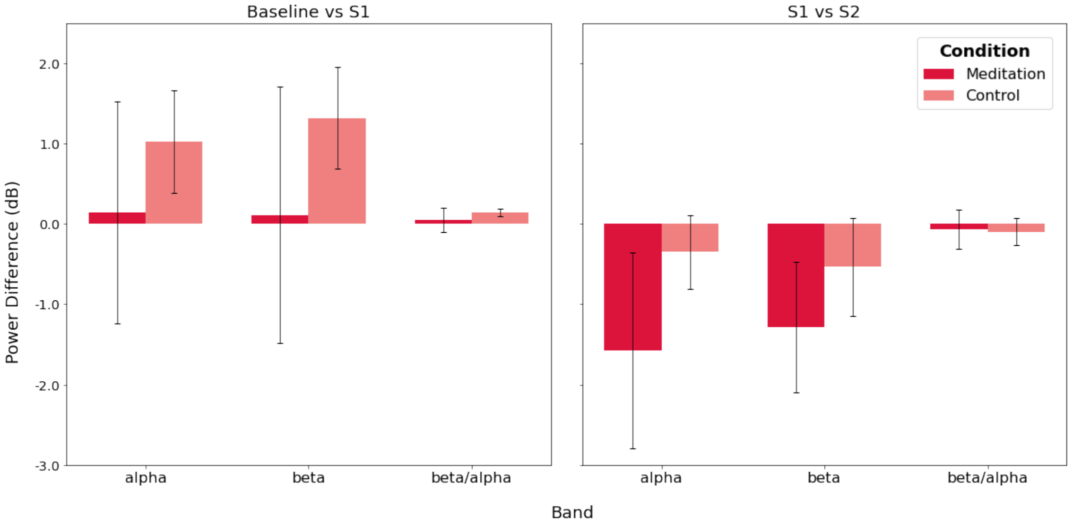

Figure 3.4: Differences in α-, β- and β/α-power between different MISTs for both the meditation and control group averaged over all four electrodes of the Muse.

diobook. Therefore, average α-power was expected to increase more after MM than after listening to the audiobook and average β-power and β/α-ratio were hypothesized to decrease more after MM than after listening to the audiobook.

4.1 Interpretations

The effects of both MM and stress on brainwaves have been explored in former research, although without consensus. However, notably, no study has been performed investigating the immediate neurophysiological effects of one MM session on psychological stress. It is necessary to address this gap because of the massive impact stress has on our lives and the need for an effective remedy. Even though people perceive less stress after meditating, this effect has not yet been studied in the brain. To examine EEG-related changes in the brain after one meditation session, the current study conducted an EEG experiment while inducing stress.

This thesis attempted to induce stress by replicating the MIST as performed by Al-Shargie et al. (2016). Al-Shargie et al. (2016) found that β-power increased and α-power significantly decreases when experiencing stress. In their study, α rhythm showed a more significant response to mental stress than β rhythm. These results are in line with the study of Alonso et al. (2015) who found a decrease in high α and an increase in high β as a result of stress.

These observations were not visible in the results. After adding the stressors, α-power did not show a stronger change than β-power. Also, the direction of change in α-power was opposite to the observations of Al-Shargie et al. (2016) and Alonso et al. (2015), showing an increase in response to stress. On the other hand, the hypothesized increase in β-power when experiencing stress was confirmed by our results. Additionally, in both experiment conditions, β-power decreased significantly after the listening task. This aligns with the results of Al-Shargie et al. (2016) and Alonso et al. (2015) as the reported stress levels after the listening task were significantly lower. However, the fact that β-power showed a significant decrease for both MM and control shows that this reduction of stress might be the result of a learning effect.

The fact that Al-Shargie et al. (2016) looked specifically at α-power in the PFC, while the current paper averaged over both the PFC and TPJ, may be a possible explanation for the differing outcomes. The split view line plots of α and β activity in the PFC and TPJ is visible in appendix D. α-Power measured by the two electrodes located at the PFC, also shows an increase-decrease trajectory. However, the fact that only two electrodes where included in this region and that one of the

		Expected direction	Frontal	Temporoparietal	Both
Meditation					
Alpha	Baseline vs S1	Decrease	$p_w = .36$	$p_{t_{rel}} = .33$	$p_w = .38$
	S1 vs S2	Increase	$p_{t_{rel}} = .50$	$p_{t_{rel}} = .48$	$p_w = .49$
Beta	Baseline vs S1	Increase	$p_{t_{rel}} = .31$	$p_w = .34$	$p_{t_{rel}} = .22$
	S1 vs S2	Decrease	**$p_{t_{rel}} = .01$**	**$p_{t_{rel}} = .01$**	**$p_{t_{rel}} = .008$**
Beta/Alpha	Baseline vs S1	Increase	$p_m = .42$	$p_{t_{ind}} = .25$	$p_{t_{ind}} = .36$
	S1 vs S2	Decrease	$p_m = .50$	$p_{t_{ind}} = .19$	$p_{t_{ind}} = .30$
Control					
Alpha	Baseline vs S1	Decrease	$p_w = .98$	$p_{t_{rel}} = .44$	$p_{t_{rel}} = .50$
	S1 vs S2	Increase	$p_{t_{rel}} = .39$	$p_{t_{rel}} = .40$	$p_{t_{rel}} = .45$
Beta	Baseline vs S1	Increase	**$p_{t_{rel}} = .006$**	**$p_{t_{rel}} = .03$**	**$p_{t_{rel}} = .003$**
	S1 vs S2	Decrease	$p_{t_{rel}} = .11$	**$p_{t_{rel}} = .03$**	**$p_{t_{rel}} = .04$**
Beta/Alpha	Baseline vs S1	Increase	$p_{t_{ind}} = .10$	$p_{t_{ind}} = .19$	$p_{t_{ind}} = .08$
	S1 vs S2	Decrease	$p_{t_{ind}} = .24$	$p_{t_{ind}} = .28$	$p_{t_{ind}} = .25$

Table 3.1: P-values found when comparing differences in average α-, β-, and β/α-power for the different stages of MIST within the meditation and control group calculated using either an one-tailed Wilcoxon signed rank test (p_w), an one-tailed Mann-Whitney-U test (p_m), an one-tailed paired t-test ($p_{t_{rel}}$) or an one-tailed independent t-test ($p_{t_{ind}}$).

		Frontal	Temporoparietal	Both
Meditation vs Control				
Alpha	Baseline vs S1	$p_m = .44$	$p_{t_{ind}} = .26$	$p_m = .41$
	S1 vs S2	**$p_{t_{ind}} = .04$**	$p_{t_{ind}} = .13$	$p_m = .48$
Beta	Baseline vs S1	**$p_{t_{ind}} = .03$**	$p_m = .43$	$p_{t_{ind}} = .07$
	S1 vs S2	$p_{t_{ind}} = .16$	$p_{t_{ind}} = .16$	$p_{t_{ind}} = .08$
Beta/Alpha	Baseline vs S1	$p_m = .07$	$p_{t_{ind}} = .37$	$p_{t_{ind}} = .10$
	S1 vs S2	$p_m = .30$	$p_{t_{ind}} = .43$	$p_{t_{ind}} = .41$

Table 3.2: P-values found when comparing differences in average α-, β-, and β/α-power for the different stages of MIST between the meditation and control group calculated using either a Mann-Whitney-u test (p_m) or an independent t-test ($p_{t_{ind}}$). These tests were two-tailed for 'Baseline vs S1'. One-tailed tests were performed for 'S1 vs S2' since differences in power were expected to be larger after MM than after listening to an audiobook.

frontal electrodes was excluded from the analysis for multiple participants may reduce the reliability of these results. Additionally, the experiment of Al-Shargie et al. (2016) was done on almost twice as many individuals, increasing its trustworthiness as well.

TuerxunWaili et al. (2020) found a positive correlation between mental stress and the β/α-ratio. This aligns with the results of Al-Shargie et al. (2016) and Alonso et al. (2015) since their observed increase in β-power and decrease in α-power would lead to an bigger value when dividing the β band by α band. Since the decrease in α-power is not visible in the results, the effect of stress and MM on the β/α-ratio is negligible. Looking carefully, there is an increase in ratio visible going from baseline to S1 and a decrease in ratio going from S1 to S2, but these changes were insignificant.

Furthermore, the insignificant improvement of accuracy after meditating contradicts the general idea present in current literature that MM improves short-term performance of students (Baranski & Was, 2019). Thus, the effects of MM on brainwaves and performance as observed by the literature is only partly visible in the results. It could be the case that, averaged over all five blocks of equations, the effect of the meditation did not last. Additionally, the stress induced by the task might have a bigger influence on brain activity than the subtle changes that MM brings about. Lastly, one single MM session might not have been enough to elucidate a change in brainwaves in the expected direction.

4.2 Limitations

There are several limitations of the current study design that could have interfered with the results.

First of all, the study is most likely underpowered. The current study only employed 13 participants, which increases uncertainty around the results. Due to this small sample size, caution must be taken when interpreting the p-values of the tests of normality and variance.

Secondly, the experiment included listening to an audiobook as control activity with the intention of occupying the participants attention, but not affecting their mood. However, listening to the audiobook may have served as a relaxing activity, resulting in smaller differences between post-audio stress levels, accuracy and brain activity between the control and test group than expected.

Furthermore, responses of individuals to the specific MM used in this study might have been different than intended as well. Even though the MM was intended to make one feel grateful for all the good things present in their lives, one participant reported to feel sad after the meditation. Fingelkurts et al. (2015) and Thakur & Baumann (2024) found that in very rare cases meditation can have adverse effects on ones mood. As the MM was not specialised to ones personal needs, this might have happened for at least one participant.

Thirdly, the evaluation of stress levels was done through only one question. This assessment might not have been sufficient for the participants to adequately indicate the level of stress they experienced during the MISTs. Additionally, stress levels were not assessed before and after the baseline. This could have given a better picture of the mood participants were in when they entered the experiment. Furthermore, self-assessed stress levels will always be relative per individual and thus hard to compare between individuals. As Noushad et al. (2021) indicated, interpersonal differences in response to a stressful situation will lead to big differences in brainwaves even when presented with the same type of stressors. Like they suggest, participants might have experienced different levels of stress as a result of the stressors in the MIST which may have lead to the non-uniform results.

Fourth, although convenient in use, the Muse has been reported to be less reliable than research grade EEG devices. Sawangjai et al. (2019) observed higher variation of signals and increases in broadband power in Muse recordings compared to research grade EEG devices. Additionally, they found the Muse headset to report inconsistent EEG data. This could be the result of incorrect placement of the Muse headset on the head. The current study has experienced this when evaluating the recorded EEG signals. Multiple channels had to be excluded due to misplacement of the electrodes or noisy signals provided by the electrodes. Additionally, Acabchuk et al. (2020) have pointed to the unreliability of the Muse because of its limited number of electrodes. This fails to honour the complexity of the human brain. They emphasize the need for caution in interpreting the EEG outcomes of such consumer-grade devices.

Fifth, for most participants at least one EEG channel was removed from their analysis. This led to an uneven number of channels for those participants and thus unequal contribution of both hemispheres to the averaged power bands. This might reduce the reliability of the averaged α-, β- and β/α-power further.

Sixth, EEG epochs were only evaluated in three batches of five - for the baseline, S1 and S2. Bad epochs were assumed to be averaged out by the rest of the batch. Thus, epochs were not assessed individually and bad epochs were not removed. Additionally, for some EEG recordings a peak in the PSD was visible around 22 Hz, which was not filtered out before processing the data. Cleaning out the data further might have improved the results.

4.3 Implications

Despite these limitations, clear trends in α- and β-power can be observed. Although insignificant, both powers seem to decrease more after meditating than after listening to an audiobook. This effect was expected for the β band, but not for the α band. The bigger increase in α- and β-power in the control group when adding stressors was also not expected and might be due to chance. In order to find a appropriate explanation for this, further investigation is necessary.

Despite the inconclusive findings, this study has opened the doors for more thorough research on the neurophysiological effects of MM on stress. As the results show, MM does significantly reduces stress levels during a stressful task. The corresponding decrease in β-power is an interesting observation useful to study mental stress further. It might shift the attention on the α band more to the β band when trying to observe stress.

The observed effect of MM in the brain in combination with its proven effectiveness in intervention-based studies could lead to the use of MM as a more preventive type of treatment against psychological stress and all the resulting diseases.

4.4 Future research

More trustworthy results on this topic might be found in future research when making some adaptations to the current study. Firstly, including more frequency bands which have been shown to respond to MM and stress will give a broader and more insightful picture of the neurophysiological effects of MM on stress. For instance, specific focus could be placed on high α- and high β-power as Alonso et al. (2015) proved their reactiveness to mental stress. Furthermore, the θ frequency band has shown to be involved in mental stress (Noushad et al., 2021) as well as in meditative states of mind (Ahani et al., 2014; Lutz et al., 2007; Tang et al., 2009). Looking into the γ band might not be the most insightful measure for stress but it does give a good indication of an individual's meditative state of mind (Lutz et al., 2007). Additionally, the unreliability concerns of the Muse in combination with the limited number of electrodes in the relevant brain regions might suggest the use of a more extensive research grade EEG recording device. Also, to increase reliability of the current study further, a bigger sample size is necessary.

To investigate the effectiveness of MM against mental stress it is useful to compare meditation to other stress relieving techniques or to a different control activity. For instance, using podcasts self-chosen by participants as an active control activity will most likely increase their participation in the audio task and might diminish the relaxing effects that the audiobook had on some of the participants. Once the effect of MM on mental stress is more clearly defined, comparing this effect to the effect of other stress relieving techniques will give a better picture of its effectiveness and the scale with which it should be recommended to individuals.

5 Conclusions

Previous studies have shown that MM can reduce psychological stress and that stress has been linked to a decrease in α band power, an increase in β band power and an increase in the β/α-ratio. The immediate effect of MM on these changes in brain activity has barely been researched. The current paper looked at the measurable effects of MM on mental stress using wearable EEG. A decrease in α band power and an increase in β band power and the β/α-ratio was expected when participants were put under stress and a reverse effect was hypothesized after completing one MM bout. Seven participants were put into the test group and participated in a MM. Six participants formed an active control group and listened to an audiobook instead. EEG recordings were made during three Montreal Imaging Stress Tasks, the first of which was a baseline measurement and the other two were stress-induced measurements. Average β-power significantly decreased after both the MM and the audiobook. Additionally, average β-power significantly increased in the control group when participants were put under stress. No significant differences were found for the absolute powers of α and β/α within-groups nor for the computed differences between the test and control group. However, α- and β- powers both seemed to show a greater change after meditation than after listening to the audiobook. Moreover, self-assessed stress levels significantly decreased after listening to a guided MM opposed to no significant decrease after listening to an audiobook. Future research on this topic, including more EEG electrodes and preferably using a research-grade EEG device, is necessary to fill the gaps.

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A Appendix A

ID	Gender	Nationality	Age	Meditation Experience	Education
1	Male	Dutch	60	None	Master's Degree
5	Female	Dutch	22	A couple times	HBO Bachelor's Degree
10	Male	Dutch	23	None	Bachelor's Degree
12	Female	Turkish	20	None	Bachelor's Degree
13	Male	Dutch	20	A couple times	Bachelor's Degree
14	Male	Dutch	19	None	Bachelor's Degree
15	Male	Dutch	20	Once	Bachelor's Degree

Table A.1: Demographics per participant in the meditation group.

ID	Gender	Nationality	Age	Meditation Experience	Education
2	Male	Dutch	21	None	Bachelor's Degree
4	Female	Dutch	23	Once	Bachelor's Degree
11	Female	Serbian	20	None	Bachelor's Degree
14	Male	Dutch	20	A couple times	Bachelor's Degree
17	Male	Dutch	22	None	Bachelor's Degree
18	Male	Russian	20	Stopped two years ago	Bachelor's Degree

Table A.2: Demographics per participant in the audiobook group.

B Appendix B

Question	Mean ($\bar{x}$)	SD (σ)
On a scale of 1 to 5, with 1 being very low and 5 being very high, how confident did you feel in your ability to sit still and comfortably during the meditation?	4.5	0.71
On a scale of 1 to 5, with 1 being very low and 5 being very high, how easy was it for you to redirect your attention back to your breath whenever your mind wandered during meditation?	4.0	0.67
On a scale of 1 to 5, with 1 being very low and 5 being very high, how easy was it for you to direct your attention to your breath when you were instructed to do so?	4.6	0.52
On a scale of 1 to 5, with 1 being very low and 5 being very high, how aware were you of bodily sensations and your ability to focus on different parts of your body during meditation?	3.8	0.92

Table B.1: Questions, means and standard deviations (SD) of the answers for the meditation engagement assessment.

Question	Answer	Average accuracy (%)
What is the name of the wizard who visits Bilbo Baggins?	Gandalf	100
What role does the wizard play in the events leading up to the journey?	He helps organise the unexpected party	75
How does Bilbo feel about joining the dwarves on their adventure initially?	Fearful and reluctant	62.5
What is a hobbit?	A small, human-like being	75
What color is the hobbit-hole door?	Green	62.5
What did the wizard give to Old Took?	Magic diamond studs	50
What do hobbits think of adventures?	They find them unfomfortable and disturbing	87.5

Table B.2: Questions, answers and average accuracy for the audiobook comprehension assessment.

C Appendix C

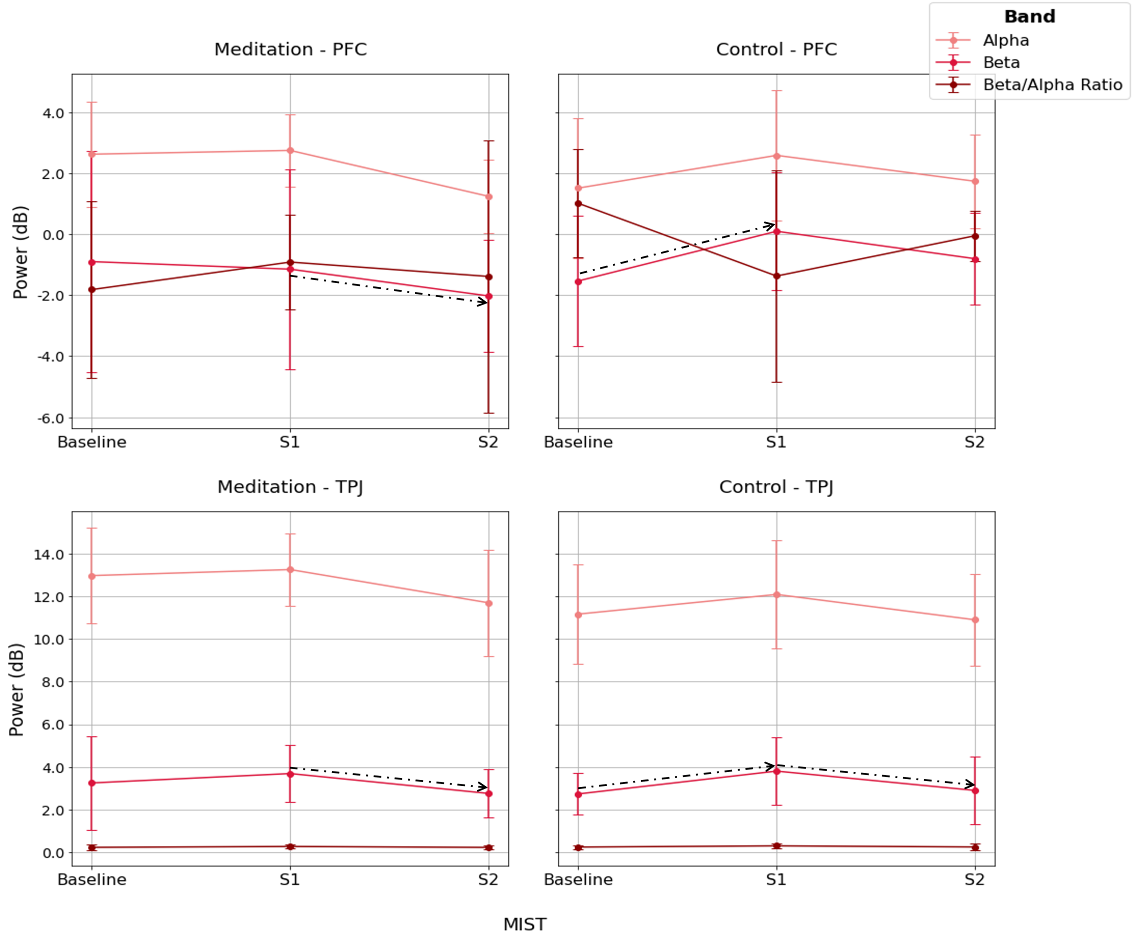

Figure C.1: Top left: line plot of the average values of α-, β- and β/α-power measured by the electrodes of the Muse headset located at the PFC. Averaged over all participants in the meditation group. Bottom left: line plot of the average values of α- and β-power and β/α-ratio measured by the electrodes of the Muse headset located at the TPJ. Averaged over all participants in the meditation group. Top right: line plot of the average values of α- and β-power and β/α-ratio measured by the electrodes of the Muse headset located at the PFC. Averaged over all participants in the control group. Bottom right: line plot of the average values of α- and β-power and β/α-ratio measured by the electrodes of the Muse headset located at the TPJ. Averaged over all participants in the meditation group. The dotted lines highlight significant results.

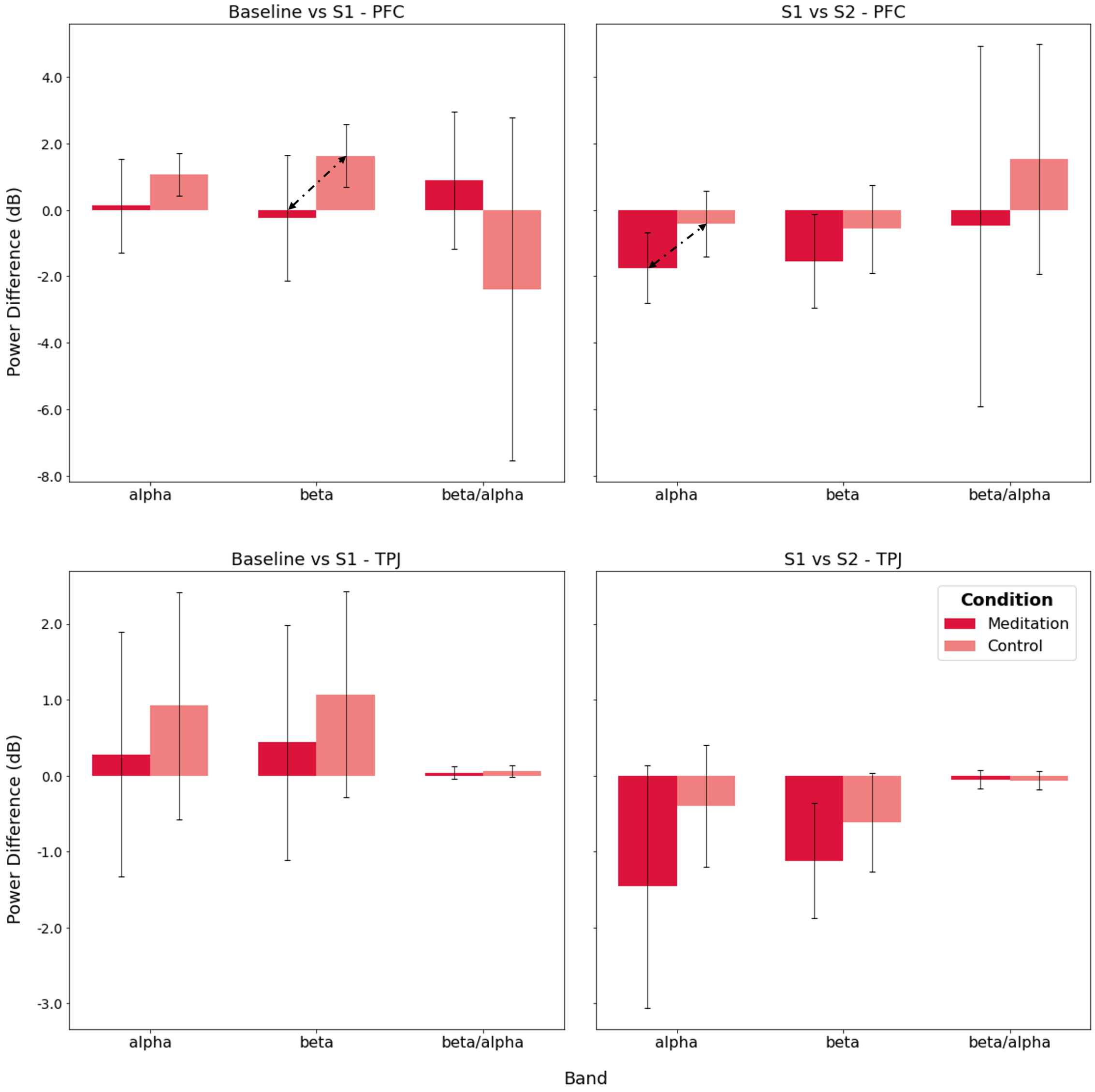

Figure C.2: Differences in α-, β- and β/α- power between the different MISTs for both the meditation (red) and control (pink) group. The dotted lines highlight significant differences. Top left: differences between baseline MIST and S1 measured by the electrodes of the Muse headset located at the PFC. Bottom left: differences between baseline MIST and S1 measured by the electrodes of the Muse headset located at the TPJ. Top right: differences between S1 and S2 measured by the electrodes of the Muse headset located at the PFC. Bottom right: differences between baseline S1 and S2 measured by the electrodes of the Muse headset located at the TPJ.