September 2014

Mindfulness Meditation versus EEG-Alpha Neurofeedback: The Role of EEG-Alpha Enhancement in Attentional Control

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MINDFULNESS MEDITATION VERSUS EEG-ALPHA NEUROFEEDBACK: THE ROLE OF EEG-ALPHA ENHANCEMENT IN ATTENTIONAL CONTROL

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Masters of Science

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Abstract

This thesis directly compared two active interventions known to enhance the EEG-Alpha rhythm, mindfulness meditation (MM) with EEG-Alpha enhancement neurofeedback (NFB), relative to a non-active Sham-NFB control. Seventy-three university students were randomized to one of the three 15-minute single-session interventions. Participants were subsequently compared on their ability to enhance EEG-Alpha amplitude as well as regarding Stroop behavioural performance, EEG event-related potentials, and EEG-Alpha event-related desynchronization (ERD) as markers of attentional control. Participants randomized to MM, NFB, and Sham did not differ in their ability to modulate the EEG-Alpha rhythm post-intervention. However, enhancements in EEG-Alpha amplitude were seen within the MM and Alpha-NFB groups during these interventions. Participants randomized to MM and NFB exhibited reduced ERD during performance of the Stroop task, interpreted as reflecting reduced cognitive effort required for task performance. However, these were not accompanied by any group differences in Stroop behavioural performance or P300 amplitudes. This study provides preliminary support for the therapeutic potential of single-session treatments that target the EEG-Alpha rhythm, such as MM and NFB, to influence neural processes underlying attentional control. Further evaluation of the benefits of these interventions across multiple sessions is indicated.

Keywords

Mindfulness Meditation, Neurofeedback, EEG, Alpha Rhythm, Attentional Control, Event-Related Desynchronization, Event-Related Potential

Co-Authorship Statement

I hereby declare that this thesis incorporates material that is the result of joint research undertaken by the author, Theodore Chow, in collaboration with the co-investigator, Tanaz Javan, under the supervision of Dr. Paul Frewen. This joint research provided the basis for two Masters theses within the Western Graduate Program in Neuroscience. The key ideas, primary contributions, experimental designs, data analysis and interpretations that are presented are unique to the current thesis and its respective topic, and were performed by the author, Theodore Chow, as supervised by Professor Frewen. The contributions of the co-investigator, Tanaz Javan, were in terms of participant recruitment and joint data collection.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

Acknowledgements

This successfully completed thesis would not have been possible had I not had the fate and fortune of having a great number of wonderful individuals deeply touch my heart during this wonderful journey.

First and foremost, I would like to thank my supervisor, Dr. Paul Frewen. Two years ago, he welcomed me, quite serendipitously, into his lab and gave me the opportunity to study something I had dreamed of ever since I encountered mindfulness. My dream of studying and finding my place within the field of neuroscience and mindfulness has been fulfilled, thank you. Paul, you are not only a consistently supportive and understanding supervisor, but now a lifelong, loving friend as well. I will always cherish our experiences together.

I would also like to thank my advisory committee for all their help editing and revising my proposals and thesis drafts: Drs. Marc Joanisse, Derek Mitchell, and Scott MacDougall-Shackleton. Dr. Joanisse, your expertise with all of the technical aspects of EEG processing, and for responding to my numerous emails so quickly and consistently, is deeply appreciated. Dr. Debra Jared, thank you for your kindness and allowing us to share the EEG Lab space. To my examiners: Drs. Ruth Lanius, Derek Mitchell, and Ross Norman. Thank you for all of your positive feedback and comments on how I can bring my research into the future. Dr. Tomas Ros, thank you for your support on EEG processing and neurofeedback. And finally, I am grateful to Ms. Carol Anderson and the UWO Neuroscience department for her support, comfort and reassurance when I needed it most.

My wonderful lab partner, Tanaz Javan. Two years ago, I would not have guessed our relationship would develop into one so close and meaningful. Your support in all aspects of my life kept me going through all the difficulties. You are now and forever my family. I thank both you and your mom, Auntie Shahnaz, for treating me like one of your own and always feeding me such delicious food (and now I am part-Persian!).

The Lanius lab: Ruth, Suzy, Stephanie, Nancy. Thank you for welcoming me into your happy, food-loving family. I felt right at home. Thank you for all the laughs, support, and hugs these past two years. I have learned a lot and gained tremendous experience from your lab. Thank you for all the wonderful opportunities and trusting me with your work.

Finally, I want to thank my family. Mom and dad: thank you so much for giving your support to help me pursue my dreams of studying mindfulness and neuroscience. I am forever grateful for your support and unconditional love. I am really fortunate to have both of you as my parents. Amy, Jeff, Nathan (and now Everett): you guys were my fountain of regeneration every weekend I came back home. Yes, even with my part-time shadow. Thank you for all the love (and Saturday afternoon dim sum!). To my closest friends, Auntie Ludia and Stephanie: I will always cherish the warmth and heartfelt support you provided me. You both have very kind hearts, and I am very grateful for your kindness and everything that I have learnt from you. Sameer: my brother, we have been through so much and you are a source of constancy in my life. Thank you for so many years of love and understanding.

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List of Abbreviations

The following table describes various abbreviations and acronyms used throughout the thesis. The page on which each one is defined or first used is also given.

Abbreviation	Meaning	Page
MM	Mindfulness Meditation	1
NFB	Neurofeedback	2
MBSR	Mindfulness Based Stress Reduction	2
MBCT	Mindfulness Based Cognitive Therapy	2
MBAS	Meditation Breath Attention Score	3
EEG	Electroencephalography	5
ERD	Event-Related Desynchronization	6
ERS	Event-Related Synchronization	6
ERP	Event-Related Potential	8
ADHD	Attention Deficit Hyperactive Disorder	12
DASS	Depression Anxiety Stress Scale	21
POMS	Profile of Mood States	22
FFMQ	Five Factor Mindfulness Questionnaire	23
TMS	Toronto Mindfulness Scale	24

Chapter 1 - Introduction

The Eastern tradition of mindfulness meditation (MM) has recently emerged in Western psychology as an increasingly popular approach to increasing well-being. Indeed, many studies document the benefits of practicing MM for reducing depression, anxiety and stress in both clinical (Hofmann, S.G. et al., 2010) and non-clinical populations (Eberth & Sedlmeier, 2012). On the surface, the practice of MM itself is inherently simplistic, as it does not require an understanding of the historical Eastern philosophies underlying concepts such as meditation and mindfulness. In fact, MM can be essentially understood as a process involving training the self-regulation of attention, where a practitioner's task is to consistently sustain attention on a single object for a duration of time (Lutz et al., 2008). As such, it has been hypothesized that a unique psychological mechanism by which MM practice can improve well-being must come from this development of attentional control.

A robust change in the EEG-alpha rhythm (8-12Hz) has been associated with MM practice, where parietal alpha amplitudes are typically seen to increase during practice (Cahn and Polich, 2006). Moreover, experienced meditators exhibit a stable shift in their resting EEG topography, with pronounced alpha amplitudes at baseline resting periods seen in frontoparietal regions, relative to controls (Aftanas & Goloshekin, 2003). Interestingly, the alpha rhythm has itself been documented to play a significant role in attentional processes such as internalized attention and top-down attentional control (Cooper et al., 2003; Klimesch, 2007). Whereas states involving internalized attention produce tonic increases in alpha amplitude, cognitive tasks requiring attentional control show phasic increases in alpha amplitude preceding experimental stimulus presentation. It has been suggested that this stimulus-preceding increase in alpha amplitude reflects the top-down control of attention in preparation for successfully responding to the stimulus in a task-relevant manner (Klimesch, 1999, 2007). Taken together, a unique neuropsychological mechanism underlying MM may be the regulation of attentional control, which may be reflected through both tonic and phasic regulation of EEG alpha oscillations. However, the change in alpha amplitude associated with MM practice can only be seen as an indirect consequence of attentional training. As such, a provocative question is whether the direct self-regulation of EEG alpha oscillations can have similar benefits for attentional processes.

Neurofeedback (NFB) is a brain-computer interface used to allow the direct self-regulation of EEG rhythms. This is accomplished through real-time displays of EEG brain rhythm activity in the form of visual and/or auditory feedback stimuli, subsequently used by individuals for the self-regulation of EEG-rhythm. As such, whereas MM indirectly enhances alpha amplitudes through its training of attention, NFB training can teach individuals to directly enhance their EEG alpha amplitudes.

The primary objective of our study was to compare two active interventions known to enhance the EEG-alpha rhythm, namely MM and EEG-alpha enhancement NFB, with a non-active Sham-NFB control condition on their ability to improve attentional control. As the two active interventions may share similar neurophysiological mechanisms of EEG-alpha enhancement, we hypothesized that both MM and NFB would improve Stroop performance and affect neurophysiological markers of attentional control during Stroop performance, specifically EEG event-related potentials (ERP) and EEG event-related alpha-desynchronization (ERD) relative to Sham-NFB; the potential advantage of NFB versus MM on these outcomes was also assessed. Our secondary objective was to further compare the relative efficacy of these interventions at enhancing the EEG-alpha rhythm during the intervention, as well as the degree with which these enhancements are sustained at the post-intervention baseline. We hypothesized that the active interventions, MM and NFB, would increase alpha amplitudes during and at post-intervention baseline to a greater degree than the non-active Sham-NFB control group.

1.1 The Study of Mindfulness Meditation

Studies increasingly document the broad benefits of mindfulness meditation (MM) practice for improving emotional well-being and cognitive function (Eberth & Sedlmeier, 2012; Sedlmeier, P., et al., 2012) as well as treating a variety of psychological and physical disorders (Baer, 2003; Chiesa & Serretti, 2010). Indeed many modern psychological interventions incorporate elements of MM, for example, *Mindfulness-Based Stress Reduction* (MBSR; Kabat-Zinn, 1994, 2003) and *Mindfulness-Based Cognitive Therapy* (MBCT; Teasdale, J.D., et al., 1995). The most robust effects of MM-based psychotherapy include decreasing negative emotions and increasing psychological well-being across both clinical (Hofmann, S.G. et al., 2010) and non-clinical populations (Eberth & Sedlmeier, 2012). Using mean weighted effect

sizes, a meta-analytic review by Hofmann et al. (2010) found MM therapy to be moderately effective for improving anxiety (g = 0.63) and mood symptoms (g = 0.59) from pre- to post-treatment in patients with various psychological disorders. Similarly, a moderate effect for stress and anxiety reduction was found in meta-analyses of MM therapy for non-clinical populations by both Carmody and Baer (2003, d = 0.66) and Eberth et al. (2012, d = 0.80). Although these findings are encouraging, most studies of MM therapy evaluated MM practices within the context of general treatments that include several different therapeutic elements (e.g, psychoeducation and yoga). Therefore, observed therapeutic effects cannot be unequivocally attributed to the practice of MM alone. Research concerning the unique benefit of MM for depression, anxiety and stress reduction, independent of nonspecific therapy factors, is sorely needed.

From a traditional Buddhist perspective MM is a means for developing the precision of attention so that it becomes a more reliable instrument for introspective examination (Wallace, 1999). MM is said to develop the psychological state of *mindfulness*, a state characterized by non-judgmental and non-elaborative receptive awareness of present moment experience (Bishop, et al., 2004; Kabat-Zinn, 2003, Melbourne Academic Mindfulness Interest Group, 2006). MM typically involves teaching an individual to sustain their attention moment by moment on a chosen object, such as a subset of localized sensations caused by respiration (Lutz, A., et al., 2008). Instructions are generally for participants to sit quietly while observing the natural rhythm of their own breath sensation localized at their nostrils or abdomen. When attention naturally wanders to distracting thoughts or feelings, participants are instructed to acknowledge and observe them without judgment and gently redirect their attention back to the process of their breathing. This process is repeated each time the mind wanders to distractions, thereby also developing a person's continuous awareness of their ongoing stream of thoughts, feelings and physical sensations (Kabat-Zinn, J., 1994). As such, capacities for vigilant monitoring and error detection of distractors (e.g. mind wandering) are developed. Disengagement from distractors requires suspension of any reactive judgment, avoidance, or elaboration towards the potentially unpleasant sensations or emotions that arise in conscious experience, thereby training the non-judgmental state of openness and acceptance.

People are thought to vary in terms of their susceptibility to mind-wandering. As such, our lab developed the *Meditation Breath Attention Score* (MBAS; Frewen et al., 2008, 2011,

2014) as a self-report measure of the degree with which participants are able to sustain their attention toward their breathing during the practice of MM. Meditation bells are sounded at pseudo-random intervals throughout a MM session, at which times participants self-report whether their attention was directed toward the intended focus (their breath) or if instead they had become distracted by mind-wandering. In this way, we can measure the ability of each participant to sustain attention toward their breath during MM, and accordingly their ability to disengage the natural tendency for habitual mind-wandering.

MM and attentional control

One of the fundamental processes occurring during MM practice is therefore thought to involve the development of attentional control. It is therefore reasonable to predict that a unique psychological mechanism by which MM therapy could improve psychological well-being is by virtue of the attentional training inherent during practice. Indeed studies on cognitive-emotion interactions have proposed that the ability to control attention can be used to filter intrusive emotional and mental information in favor of optimizing and enhancing subjective well-being (Wadlinger and Isaacowitz, 2011).

Certain parallels can be noted between the processes involved in MM and recent neuroscientific conceptualizations of attention. Indeed the ability to sustain attention on a single object for continuous periods during MM practice requires the development of three regulatory skills: 1) alerting, 2) orienting, and 3) conflict monitoring (Slagter, H.A. et al., 2011). During the first skill, *alerting*, the MM practitioner maintains a vigilant or alert state of preparedness for distractions such as mind-wandering, valenced emotional stimuli, or other environmentally caused disturbances in attention. The second skill, *orienting*, involves the ability to selectively attend and orient attention to a subset of possible inputs. Finally, *conflict-monitoring*, allows the MM practitioner to prioritize among competing stimuli, in favor of the task-relevant goal of sustaining attention toward breath sensations. These three attentional capacities have been associated with dissociable systems in the brain in recent neuroscientific investigations of attention (Posner and Rothbart, 2007). A reasonably straightforward prediction in light of these trained processes is that MM practice should be correlated with improvements in behavioural measures of attention, such as in cognitive tasks that involve these aspects of attention.

The Stroop colour-naming task (Stroop, 1935) is paradigmatically used in psychology as a measure of selective attention and conflict monitoring performance (Carter et al., 1995). It is a cognitive task that evaluates the participants' ability to filter out irrelevant distracting semantic information from a stimulus in favor of prioritizing task-relevant visual information (Strauss et al., 2006). Distracting semantic information within the Stroop task is purposely used because it is automatically processed and cognitively biased relative to visual processing. Typically, stimuli are presented with congruent or incongruent visual and semantic information. A robust finding, referred to as the Stroop interference effect, is an increase in the number of errors and time taken to respond to incongruent conditions, relative to congruent conditions. This behavioural difference is generally thought to be due to a conflict between stimulus and response that results in competition for the allocation of attentional resources or a conflict at the level of response selection and monitoring (Badzakova-Trajkov, G. et al., 2009). Since MM practice is thought to develop the capacity for attentional control, the level of mindfulness achieved by participants may predict their performance on the Stroop task. In fact a significant positive correlation between Stroop performance and meditation experience, the latter measured using journal entries documenting minutes of meditation per day, was found in experienced MM practitioners (Chan & Woollacott, 2007). Similarly, experienced meditation practitioners recruited from retreat centres showed positive correlations between self-reported measures of mindfulness and the number of items that were correctly processed in the Stroop task (Moore & Malinowski, 2009).

1.2 EEG-Alpha Rhythms and Attentional Control

Electroencephalography (EEG) is a noninvasive method to measure brain electrical activity with the use of electrodes placed along the scalp. It is a direct measure of brain function that has been used for many applications within the neurosciences such as toward understanding cognitive processes, emotional function, dysfunction and development. The most common parameters used to characterize the normal EEG are frequency and amplitude. It is primarily using these parameters that distinct tonic psychological states have been described (Davidson, 2000). For example, in normal human adults, deep sleep or slow-wave sleep is associated with very high amplitude and low frequency waves called the delta frequency range (1-4Hz). Drowsiness or the hypnagogic transitional state from wakefulness to sleep is associated with

lower amplitude theta frequency range (4-7Hz). Of particular interest to this thesis is the alpha frequency range (8-12Hz), often termed “relaxed wakefulness” and characterized by relatively lower amplitude than that seen in the delta and theta range. Amplitudes are the smallest in the beta range (13-30Hz), which is associated with alert attentiveness.

EEG-Alpha rhythm

In the healthy awake adult at rest, the most prominent and dominant component of the EEG is the alpha rhythm (8-12Hz) (Klimesch, 1999). In fact, it was the first waveform to be described and recorded by Hans Berger (1929). Although alpha waves are present throughout the cortex, they are most prominent over the posterior parietal and occipital lobes when a subject's eyes are closed (Neidermeyer, 1993). Traditionally, the alpha rhythm was argued to reflect a generalized idling condition of the brain when it is calm and alert, uninvolved with the performance of any particular resource-intensive cognitive task (Adrian and Matthews, 1934). This is due to a common property of alpha in that its amplitude is reduced after the subject’s eyes are opened, termed ‘alpha blocking’. In support of this, many studies have noted a task-related decrease in alpha amplitude over occipital sites during visual stimulation (Mann et al., 1996) and sensorimotor areas during movement or sensorimotor tasks (Pfurtscheller et al., 1996). However, other studies identify the alpha rhythm with internalized attention and the need to filter out externally distracting stimuli. Ray and Cole (1985a, b) found increased alpha amplitude during mental imagery and working memory tasks requiring internal attentional focus and filtering of distracting task-irrelevant information, especially at parietal sites. Several studies have since observed alpha amplitude increases during mental imagery and mental rotation tasks relative to perceptual tasks (Schupp et al., 1994; Williams et al., 1995; Klimesch et al., 1990).

In an attempt to integrate these previously conflicting findings on alpha amplitude, Klimesch (1999) noted that the behavior of the alpha amplitude can be differentiated between tonic psychophysiological states such as internalized attention during mental imagery tasks versus phasic responses to individual experimental stimuli. Whereas a tonic increase in alpha amplitude is seen during continuous periods requiring internal attention such as the recitation of a sequence of mental images or sounds (Cooper et al., 2003), the behavior of the alpha amplitude is phasic during cognitive tasks, varying with the discrete presentation of a stimulus or cognitive event. During the course of a cognitive task, some event or stimulus is typically presented

requiring actual cognitive performance, relative to a resting state between responses typically involving visual fixation. Cognitive activation during the response is typically reflected in a suppression of the alpha amplitude, called an event-related desynchronization (ERD; Pfurtscheller & Lopes da Silva, 1999). During the inter-stimulus reference interval preceding each event, the subject is relaxed and awaiting the presentation of the next stimulus, which has been associated with high alpha amplitude, called event-related synchronization (ERS; Klimesch, 1999). Furthermore, the extent of the ERD during stimulus-response has been found to vary in terms of the absolute alpha amplitude measured during the baseline between events: a positive correlation has been found between the ERS and ERD (Klimesch, 1999, 2007).

Building upon the tonic increase of alpha amplitude during internal top-down attention, Klimesch (2007) hypothesized that ERS measured during inter-stimulus periods may also reflect internal, top-down control of attention and readiness to perform a new task. On the other hand, ERD during actual stimulus presentation is associated with, and a good predictor of, task performance. Therefore, if attentional control and vigilance is strong prior to task responding, EEG-Alpha ERS will be high, and ERD and task performance will be subsequently high as well. For example, Klimesch et al. (1997) found that ERD during a semantic judgment task (whether a pair of words were semantically congruent) is significantly larger for participants responding with greater accuracy. Further, significant positive correlations were found between ERD and semantic memory performance. Doppelmayr et al. (2005) replicated this effect and found that participants with higher IQs exhibited more extensive alpha ERD during semantic processing relative to low IQ participants.

Lower (8-10Hz) and upper (10-12Hz) EEG-Alpha sub-bands

Interestingly, cognitive research observing EEG-Alpha ERD/S patterns revealed differential patterns of alpha desynchronization when the full (8-12Hz) alpha band was sub-divided into narrower frequency bands of 8-10Hz (lower alpha) and 10-12Hz (upper alpha) (Klimesch, 1999). Extensive research by Klimesch and colleagues found evidence that alpha desynchronization is not a unitary phenomenon, where distinct patterns of ERD between the two sub-bands reflect functionally different cognitive processes. Whereas the lower (8-10Hz) alpha band desynchronizes during task periods that require attentional processes such as selective attention, alertness and vigilance, the upper (10-12Hz) alpha band desynchronizes during

cognitive processing of specific task requirements such as semantic and working memory processes (Klimesch et al., 2007). For example, in a modified auditory oddball task, lower 8-10 Hz ERD was seen after the onset of a warning signal reflecting enhanced alertness, vigilance and expectancy, while ERD in the upper (10-12Hz) alpha band occurred during actual task performance (Klimesch, 1997, 1998). This was further reflected in the previous semantic judgment tasks where only the upper alpha band exhibited ERD during task performance. Therefore, whereas the full alpha band increases in amplitude tonically during internalized attention, phasic changes in the lower alpha band may reflect general alertness and vigilance, and increased amplitude of the upper alpha band may reflect internally focused attention required by specific task demands (e.g., semantic and working memory processes).

EEG-Alpha topography in attentional control

The top-down control of attention is not only characterized by changes in alpha amplitude as described above, but also through the topographical analysis of EEG-alpha phase dynamics between higher and lower hierarchical cortical areas (Nunez et al., 2001; Sauseng et al., 2005; Klimesch et al., 2007). When the difference in phase angle of an EEG-alpha rhythm at two distinct electrode sites is consistent across multiple trials in a cognitive task, the brain regions subserving the electrode sites are thought to be functionally related to each other and involved in task-relevant processes (Sauseng & Klimesch, 2008). This is termed high phase coherence. Further, the magnitude and sign of the phase angle difference (i.e. the phase shift) between the two electrodes is interpreted as indicating the direction of alpha wave propagation from one cortical region to the other. This phenomenon has been studied extensively and is termed traveling waves (Ito et al., 2005). In a visuo-spatial task involving the top-down control of attention, Sauseng et al. (2005) observed the topographical behavior of the EEG-alpha rhythm through both ERS/ERD and phase-dynamics. Participants were asked to either remember visuo-spatial stimuli (control condition) or mentally rotate it about a vertical axis (top-down condition). During the mental rotation condition, strong phase coherence was found between the frontal and posterior sites, indicating functional connectivity between these regions during the top-down control of attention. EEG-alpha amplitude changes in these cortical regions exhibited ERS at frontal sites and ERD at posterior sites during the top-down condition, relative to the control condition. In regards to phase dynamics, the EEG-alpha waves at these two sites exhibited a

phase-shift consistent with a traveling wave moving from the leading anterior site to the trailing posterior site. This hierarchical propagation of the alpha-wave has been demonstrated multiple times in other tasks involving top-down executive processes, where alpha has been consistently observed to propagate from higher cortical regions to lower ones (Von Stein et al., 2000; Ito et al., 2005; Halgren et al., 2002). These phase-shifts or traveling EEG-alpha waves have consistently been described to reflect waves of spreading activation moving from one area to another. Furthermore, propagation has been shown to reverse from lower cortical regions to higher cortical regions in bottom-up processing tasks, for example, from the primary visual cortex to the visual association cortex (Von Stein et al., 2000; Halgren et al., 2002). These observations highlight the importance of the EEG-alpha rhythm as a means of cortico-cortical communication, especially during top-down attentional processes requiring frontal executive activation.

P300 neurophysiological marker of attentional control

Whereas ERD and ERS reflect transient event-related changes in amplitude within specific EEG frequency bands (e.g. alpha) over time (Bressler, 2002), the event-related potential (ERP) is not specific to any frequency band and instead measures EEG brain response time-locked to the onset of a stimulus. As such the ERP is considered to be a direct result of specific sensory, cognitive, or motor events (Bressler, 2002; Luck, 2005). The signature ERP waveform in response to a stimulus reflects the flow of information through the brain associated with performance of some cognitive task. Typically, the stereotyped ERP waveform consists of a sequence of positive and negative voltage deflections on the EEG, called components. The parameters of these components, such as amplitude and latency from the time of stimulus onset, provide valuable information regarding the cognitive processes that become active as a result of the ERP-producing event. In particular, the P300 component is typically used as a marker for attentional processing of a stimulus (Polich, 2010). The ‘P300’ designation indicates that the voltage deflection of the component is positive and reaches a peak around 300 milliseconds after the stimulus onset. The P300 is the most prominent ERP component sensitive to cognitive processing (Verleger, 1988), where the amplitude of the P300 reflects the task relevance of a stimulus and P300 latency reflects the duration of stimulus evaluation (Nasman & Rosefeld, 1990; Mechlinger & Ullsperger, 1993). Discriminating whether a stimulus is relevant to the task

goal produces a robust increase in P300 amplitude (Polich, 2010). The P300 amplitude is also sensitive to the amount of attentional resources engaged during task performance. During cognitive tasks that are attentionally demanding, P300 amplitude is small and peak latency is longer since processing resources are used for task performance.

The attentional development that is trained during MM therapy is associated with differential effects on P300 parameters. The most common change seen after MM practice is a reduced P300 amplitude during cognitive task performance relative to controls. For example, in the typical oddball task, MM participants demonstrated a reduction in P300 amplitude in response to rare targets (Cahn & Polich, 2009) as well as a decrease in P300 latency (Cranson et al, 1990), relative to controls. In these studies, amplitude and latency were negatively correlated with self-reported meditation practice. This finding was also replicated in the attentional Stroop task wherein, during the presentation of incongruent stimuli, participants in the MM group exhibited a decrease in P300 amplitude relative to the control group even in the absence of significant differences in behavioural performance (accuracy or reaction time; Moore et al, 2012), interpreted as reflecting greater resource allocation and more efficient processing during tasks requiring attentional control in MM practitioners (Cahn & Polich, 2009; Slagter et al., 2007).

1.3 Mindfulness Meditation: Neurophysiological Mechanisms

The most replicated tonic EEG correlates of MM during resting baseline or during MM practice itself identified in a meta-analysis of 60 studies and 1400 participants (Cahn & Polich, 2006) included acute increases in alpha oscillation amplitude during meditation, as well as greater baseline alpha amplitudes in experienced meditators at rest (e.g., Aftanas & Goloshekin, 2003). Meditators are characterized not only by dynamic shifts associated directly with being in a ‘mindful’ state, but also by a stable change in their baseline EEG-alpha rhythm. These changes are typically seen over posterior, central, and anterior midline cortex (Cahn & Polich, 2006; Chiesa & Serretti, 2010; Lagapoulos et al. 2009). Almost all studies of EEG change associated with MM practice investigate only the full (8-12Hz) alpha band. Given that recent cognitive research has distinguished the lower (8-10Hz) and upper (10-12Hz) alpha sub-bands with distinct

attentional processes, it seems critical to investigate the effects that MM attentional training has on the alpha sub-bands. Although increases in full alpha band amplitude during MM indeed correspond to previously described correlations with internalized attention, analysis of MM practice in terms of the distinct upper and lower alpha sub-bands would provide further insight towards the neurophysiological processes occurring during MM practice.

In addition to producing tonic changes in the EEG, perhaps the most impressive evidence for a causal effect of MM treatment on the regulation of alpha oscillations comes from a recent magnetoencephalography (MEG) study phasically cueing participants to direct their attention to somatic sensations towards either their hand or foot in preparation for the detection of a light tactile stimulus administered shortly after the cue (Kerr et al. 2011). When cued towards the foot, distracting sensory information from the hand must be filtered which was indeed reflected in an alpha amplitude increase seen on the MEG of the primary somatosensory cortex hand map. The opposite was seen when cued towards hand, with decreased amplitudes in the hand map. Interestingly, MM participants showed significantly enhanced differentiation of their alpha amplitude, relative to controls, as measured by the difference between MEG-alpha during cue-hand minus cue-foot. Thus, attentional development through MM training is reflected by the practitioner's greater ability to modulate his or her alpha rhythms. These changes in alpha amplitude during and after MM practice are robust, as they do not depend on experience of the meditator, nor the meditation tradition. As such, it is plausible that a central commonality of attentional training across many meditative traditions may be related to these robust changes in EEG-alpha rhythms (Lutz, et al., 2008). Therefore the underlying neurophysiological mechanism partly through which MM practice may improve attentional functioning and emotional well-being may be through the tonic and plastic regulation of EEG-alpha oscillations.

1.4 EEG-Alpha Neurofeedback

Importantly, the change in EEG-alpha amplitude associated with MM practice can only be understood as an indirect consequence of its attentional training. As such, an appealing question concerns the consequences of the direct self-regulation of EEG-alpha on attentional processes, and whether such practices could have similar benefits to attentional control seen in MM. With the use of brain-computer interfaces, such as EEG neurofeedback (NFB), such a direct comparison of the effects of NFB and MM on the alpha rhythm and attentional control can be achieved.

Traditionally, biofeedback therapy involves the process of gaining awareness of and subsequently self-regulating physiological functions (Schwartz & Olson, 1995). This is achieved primarily through the use of instruments that monitor and display the status of peripheral aspects of the sympathetic and parasympathetic nervous system (e.g. respiration, temperature, heart rate, galvanic skin response) (Schwartz & Olson, 1995; Robbins, J., 2000). Neurofeedback (NFB) is a modality of biofeedback in which real-time displays of neural (typically EEG) activity is recorded and subsequently displayed to participants in the form of visual and/or auditory stimuli. During typical training, electrodes are placed on the scalp, with reference electrodes usually placed on each earlobe (Hammond, 2006). The brain electrical activity is recorded and amplified before being relayed to the computer where specific parameters of the raw EEG signal are filtered. Real-time, instantaneous audio-visual feedback reflecting this brain activity is fed back to the participant generating a continuous online feedback loop. These feedback stimuli are directly related and change relative to EEG brain rhythm parameters, typically the amplitude, frequency or coherence of distinct EEG components (Hammond, 2006). In this way, participants gain awareness of their brainwave patterns and the ability to modify some aspect of their cortical activity through various mental strategies, learning to modulate their degree of arousal or attention. Ultimately, the goal is for participants to learn to voluntarily self-regulate their EEG rhythms.

The underlying rationale behind NFB is based on EEG and neuroimaging research on correlates of brain pathology (e.g. ADHD, depression), accidental discovery (e.g. epilepsy), or neurophysiological correlates of cognitive states (e.g. anxiety, substance abuse). By identifying associations between unique EEG or neuroimaging correlates of healthy and pathological aspects

of behavioral functioning and cortical arousal, NFB can help train participants to achieve healthy states by mirroring the patterns of cortical activity seen in such states. Historically, the possibility for healthy individuals to perceive and obtain conscious control over the production of their brainwave activity was found using NFB of the 8-12Hz alpha EEG rhythm (Kamiya, 1968). NFB then became more popular clinically for the treatment of pathologies characterized by dysfunctional regulation of cortical arousal, such as epilepsy (Sterman et al., 1974) and attention deficit hyperactivity disorder (ADHD) (Linden et al., 1996; Luber et al., 1995). For example, it was revealed that children exhibiting scholastic and behavioural problems had EEG rhythms that were different than healthy controls, with less activity in the 12-20Hz beta sensory-motor rhythm, and more rhythmically slow 4-8Hz theta activity (Winkler, et al., 1970). These findings lead to the use of NFB to specifically enhance beta activity and suppress theta activity in children with ADHD (Linden et al., 1996). Significant improvements in attentive behavior and intellectual functioning were seen in the NFB treatment groups, relative to wait-list controls, and were attributed to attentional enhancement as a result of NFB.

The initial development of training the human EEG alpha rhythm using NFB was aimed at relieving anxiety and improving mood (Hammond, 2005; Putman, 2000). In fact, the initial development of such a protocol was based on historical meditation research showing that individuals in meditative states exhibited increased alpha amplitude activity as well as greater levels of relaxation (Kasamatsu & Hirai, 1969). Additionally, the use of NFB on controlling alpha activity in healthy subjects was associated with the subjective phenomenology of relaxation during successful regulation (Brown, 1970; Kamiya, 1969). Numerous randomized controlled studies on the ability of NFB training to reduce anxiety and depressive symptoms have since surfaced. Hardt and Kamiya (1978) tested long-term (>5 hours) NFB alpha enhancement training at central and occipital cortical sites in two groups of subjects with either high or low self-reported trait anxiety. Alpha increases in occipital and central sites ranged from 40 to 128% above average baseline that lasted for more than 2 hours after training. Although both high and low anxiety groups were successfully able to enhance their alpha rhythm, only high anxiety subjects demonstrated significant reductions in anxiety. In an elegant randomized controlled study to test for the specific effects of EEG-alpha NFB on mood, individuals with generalized anxiety disorder were randomized to either to one of three treatment conditions or a wait list control: electromyography biofeedback for muscle relaxation, EEG-alpha enhancement

NFB, EEG-alpha suppression NFB, and pseudo-meditation control (Rice, et al., 1993). Although all participants in the active treatment conditions had significant reductions in self-report for trait anxiety, only EEG-alpha enhancement NFB participants showed significant reductions in physiological responses to stressors measured through heart rate reactivity. This study particularly demonstrates, with the success of all treatment groups at reducing anxiety, the potential of common nonspecific factors that may alter cognition or subjective well-being due to the perceived success at ostensibly anxiolytic tasks. However, with the use of heart-rate response to stressors, some differential effectiveness in training between the two EEG-alpha NFB groups could be demonstrated. EEG-Alpha enhancement and suppression NFB modulated alpha rhythms in the appropriate direction reflective of their respective training. However, whereas increasing EEG-alpha significantly reduced heart-rate response, EEG-alpha suppression actually increased heart-rate response to stressors, perhaps for the first time demonstrating specific effects at training EEG-alpha rhythm. In another attempt to control for the nonspecific effects of receiving NFB, Raymond, et al. (2005) used a mock feedback condition that resembled the real NFB condition as closely as possible. A recording of the real NFB training session served as auditory feedback for the control group thus mimicking the probable characteristics of feedback that would be received from the experimental group, such as the temporal evolution of feedback during a typical session. Using a standardized self-report scale to assess mood, Raymond et al. (2005) found that real NFB caused participants to feel significantly more composed, agreeable, elevated, and confident; interestingly, mock feedback made participants feel more tired.

It is important to note that an implicit assumption underlying NFB literature that supports current NFB therapy is that the training process will lead to changes in the EEG, which in turn produces changes in behavior. Recent research shows that NFB training of various frequency bands affects spectral EEG topography in healthy participants after training, although these effects frequently do *not* necessarily correspond directly with either the frequencies or scalp locations focused on by the training parameters (Egner et al. 2004). For example, learning to temporarily enhance beta 12-15Hz activity over the sensorimotor cortex was related to post-training decreases in the same activity band in prefrontal regions (Egner et al., 2004). Encouragingly, studies observing NFB training on the 8-12Hz alpha band alone have received more success in producing post-training EEG changes directly reflecting the training parameters (i.e., alpha), as seen above and according to more recent research (Dekker et al. 2014; Zoefel et

al. 2011; Boxtel et al. 2012). However, almost all study designs using NFB to train the EEG-alpha rhythm have used multiple sessions (at least 6) over the course of many weeks. To the best of our knowledge, only a single prior study incorporated a single, brief 20-minute NFB session design where the suppression of EEG-alpha amplitude at the central parietal electrode (Pz) was accomplished (Ros et al, 2013). NFB participants were indeed successful at reducing their target alpha amplitude throughout the 20-minute training period relative to a Sham-NFB control group.

1.5 EEG-Alpha Neurofeedback: Attentional Control

Given the historical use of NFB to improve attention as a treatment for ADHD, along with the previously presented literature relating the EEG-alpha rhythm with attention, a number of studies have attempted to investigate the potential of NFB for improving aspects of attentional performance in healthy subjects. As mentioned earlier, EEG-alpha amplitude is typically seen to increase during tasks requiring internalized control of attention, or executive attention. Similarly, studies have positively correlated EEG-alpha amplitude with cognitive performance (as reflected through inter-stimulus ERS) and negatively with age (Klimesch, 1999). Angelakis et al. (2007) attempted to use NFB to increase alpha amplitudes in elderly participants and found improvements in attentional control (using the Stroop task) and sustained attention (go/no-go task) after successful enhancements of alpha amplitude. However, instead of training the whole 8-12Hz alpha band, Angelakis et al. trained the specific frequency within the alpha band (8-12Hz) exhibiting the largest amplitude, termed the individual peak alpha frequency, as this peak alpha frequency varies between participants. Similarly, specific training of alpha amplitude enhancement in only the upper sub-band of 10-12Hz has shown cognitive improvements in a mental rotation working-memory task (Hanslmayr et al., 2005; Zoefel et al., 2011). Taking into consideration the increase in EEG-alpha amplitude across the full 8-12Hz band during tasks requiring internalized attention, including MM, it is surprising that few studies have attempted to use NFB to directly modulate the full alpha band and observe subsequent effects on attentional control.

1.6 The Present Study

Based on the literature reviewed above, the EEG-alpha rhythm is thought to play a role in attentional control and subsequently mood through the effective deployment of attention in guiding emotional regulation processes. As such, a strong rationale arises towards investigating interventions that are known to involve neurophysiological processes of EEG-alpha enhancement in terms of their potential for improving attentional control performance and mood. Relatedly, investigation of these interventions will help provide insight towards the relative plasticity of the EEG-alpha rhythm and the possibility for an individual to produce sustainable and lasting enhancements in their EEG-alpha rhythm after a brief single session intervention. This study therefore attempts to compare two interventions, MM versus alpha-enhancement NFB, on their ability to enhance the EEG-Alpha rhythm and effect behavioural and neurophysiological markers of attentional control as measured by Stroop performance, relative to a non-active Sham-NFB control group. Specific lower (8-10 Hz) and upper (10-12 Hz) alpha sub-band analyses will also be investigated to determine distinct attentional processes that may occur during the respective interventions. In this way, the role and indeed importance of the EEG-alpha rhythm in modulating attentional control and mood can be better understood.

1.7 Summary and Hypotheses

Attentional control development may help guide individual emotional regulation processes and ultimately aid in optimizing an individual's subjective experience. A proposed psychological mechanism of MM therapy for improving emotional well-being can be attributed to the cognitive training of attention inherent to the process of meditation. This may be reflected in enhancement of the EEG-Alpha rhythm typically associated with MM practice. The study of NFB therapy can build on the EEG-Alpha and attentional control relationship seen in MM by directly self-regulating the alpha rhythm, independent of any specific cognitive training of attentional processes. As such, a strong rationale arises towards comparing the ability of MM and NFB to improve attentional control performance and mood outcomes. Despite the extensive literature behind MM and EEG-alpha NFB therapies alone for improving attentional control and

mood, no studies have attempted to directly compare them and integrate these findings in terms of neurophysiological mechanisms and outcomes. By comparing these therapies, further insight can be gained and supplement evidence towards a potential relationship between EEG-alpha in regulating attentional control and subsequently mood. Relatedly, it is important to observe the sensitivity of the EEG-alpha rhythm to plasticity after administration of a brief single session intervention (i.e. the potential for an individual to produce sustainable enhancements in their EEG-alpha rhythm after a single session of MM or NFB).We therefore designed a randomized controlled trial directly comparing the attention and emotional outcomes of either administering a single 15-minute session of MM or EEG-alpha NFB enhancement, relative to a Sham NFB condition. This trial aims to provide a better understanding of the psychological, neurocognitive and neurophysiological outcomes of MM and NFB, as well as to elucidate important biomarkers associated with treatments that target attentional control and emotional well-being. This will support their potential use as therapies for enhancing cognitive performance and emotional well-being in both clinical and nonclinical populations.

Hypotheses

Our primary hypotheses concern the comparison of the active interventions of MM and EEG-Alpha NFB relative to the non-active Sham-NFB control group. We predicted that MM and NFB would impact performance on the Stroop task relative to Sham-NFB control, as assessed behaviourally (accuracy and reaction time) as well as via EEG measures, specifically, the ERP and alpha-ERD. We also predicted that the active interventions would enhance the EEG-Alpha rhythm during training as well as during post-training baseline to a greater extent than the non-active Sham-NFB control group. Comparisons between the two active interventions, MM and NFB, were for the most part exploratory but further allowed investigation of the potential advantage of NFB relative to MM on these outcomes, as a more direct means of self-regulating the EEG alpha rhythm.

Chapter 2 - Methods

2.1 Participants and Setting

Seventy-three healthy adults (23 males; age ranged between 18-30 years) were recruited from the University of Western Ontario (UWO) undergraduate Psychology research participation pool. Study information was publicized to students using: 1) the UWO online SONA system for administering research studies to Psychology students; and 2) via email to upper-year Psychology students. Students were subsequently able to volunteer to participate using either the SONA system or directly to the researchers via email. Inclusion criteria were a lack of prior experience with MM practice or NFB. All participants recruited for the study were currently enrolled as an undergraduate student at UWO but were not necessarily in the Psychology program. Participants received partial course credit for completing the study.

Participants were randomly assigned to either the MM group (n=25), EEG-Alpha enhancement NFB group (n=24), or the Sham NFB group (n=24). It should be noted that a fourth group, involving EEG-Alpha desynchronization, was also included, although analysis of this group was determined beyond the scope of this thesis. It should further be noted that a small number of participants also volunteered to complete a follow-up study involving additional sessions of their respective interventions conducted over the course of 8 weeks, although a generally low enrolment rate coupled with a high percentage of drop-outs preclude reliable conclusions; as such, analysis of data collected longitudinally was also determined beyond the scope of this thesis.

Participants were excluded from final analyses based on outliers in depressive symptoms (DASS-Depression scores, all observed within the Alpha-NFB group, n=3) and EEG recording problems (Alpha-NFB, n=3; Sham-NFB, n=3). As such a total of sixty-seven participants were included in the final analysis (MM, n=25; Alpha-NFB, n=21; Sham-NFB, n=21). The study took place within the UWO campus in the Social Sciences Centre Electrophysiology Laboratory.

2.2 Ethics Approval and Informed Consent

This study was approved by the University of Western Ontario Health Sciences Research Ethics Board (HSREB, Study ID: 103335). The HSREB is organized and operates according to the Tri-Council Policy Statement: *Ethical Conduct of Research Involving Humans* and the *Health Canada Good Clinical Practice* and the applicable laws and regulations of Ontario.

All participants gave informed consent after being provided with detailed information regarding the background of the study, potential risks and discomforts, and confidentiality. All participants were allowed to withdraw from the study at any time during the duration of the study and were free to withdraw their data should they wish; no participants were withdrawn from the study and no adverse events were recorded.

2.3 Interventions

Mindfulness Meditation (MM) and Meditation Breath Attention Scores (MBAS)

Participants in the MM group were introduced to a simple mindful breathing meditation administered using standard published procedures (Frewen et al., 2008, 2011, 2014) by M.Sc. student researchers Theodore Chow and Tanaz Javan as supervised by Dr. Paul Frewen. Participants were instructed to focus their attention toward the sensation of their breathing at their nostrils. They were asked to refrain from manipulating their breathing in any form, and instead to allow their natural breathing rhythm to occur. They were instructed that, whenever they became aware that their attention had wandered from a focus on breathing sensation they should simply redirect their attention back to the sensation of their breathing. In addition to focusing their attention toward their breath, participants were instructed to observe any distracting thoughts, feelings, or sensations without judging, evaluating, or elaborating on them. This meditation is in line with recent psychological conceptualizations of MM that emphasize the development of attentional abilities combined with a specific, non-judgmental attitude toward the different mental experiences that may arise during MM (Slagter, H.A., et al, 2011; Lutz, et al., 2008).

Participants were given 3-minutes prior to the start of the meditation to adjust to the environmental setting. MM was practiced while participants were seated comfortably on a chair, with arms rested on their lap. Subsequently, a 15-minute timed MM began. Three consecutive meditation bells were sounded to mark the beginning and ending of the MM. Additionally, a single meditation bell was sounded approximately at 3-minute intervals throughout the session (5 bells in total). During these interval bells, participants were cued to self-report whether at these moments their attention was directed towards their breathing (intended focus), scored 1, or if instead at these moments they were presently distracted by other thoughts, feelings, sensations, or other experiences (i.e., mind-wandering), scored 0. This was done by placing a standard QWERTY keyboard on their lap, where participants pressed the keys "l" or "s" if their attention was on their breath or otherwise, respectively, whilst keeping their eyes closed. This data collection procedure provides the *Meditation Breath Attention Score* (MBAS) self-report measure, previously used to self-report relative concentration levels (versus proneness to distractibility or mind wandering) during the practice of MM (Frewen et al., 2008, 2011, 2014). In other words, the MBAS was originally designed to operationalize a performance variable relating to MM practice indexing the extent of concentration or attentional control present during the meditation, with the MBAS assessing the participants' ability to sustain their attention toward their intended focus (i.e. breathing) during the MM practice, and accordingly their ability to disengage from mind wandering. Calculation of the MBAS involved simply summing the number of times out of five that participants reported that they were attending toward their breath during each of the five meditation bells. In support for the construct validity of MBAS, previous studies identified positive correlations between MBAS and responses to the *Five Factor Mindfulness Questionnaire* subscale "Acting with Awareness," as well as self-report measures relevant to the experience of mindfulness (Frewen et al., 2008, 2010, 2014). MBAS were also found to improve with repeated practice of MM in a previous study (Frewen et al., 2014). Previous undergraduate samples have achieved a mean MBAS score of 2.36 (SD = 1.24, Frewen et al., 2008), and typically ranged between 0 and 3 (M = 1.74, SD = 0.88, Frewen et al., 2011).

EEG-Alpha Neurofeedback (NFB)

Participants in the NFB group were trained to enhance their EEG-alpha amplitude at their scalp Pz site (midline parietal cortex), where the EEG-alpha rhythm is typically maximal

(Ergenoglu et al. 2004). To accomplish this, a single electrode was placed at the Pz site according to the 10-20 internationally standardized system for electrode placement. Prior to electrode placement, skin was prepared with NuPrep (Weaver and Company, US), a mildly abrasive skin cleaner to help improve impedance and conductance of electrodes. Electrodes were then affixed with adhesive conductive paste (Ten20, Weaver and Company, US). The electrode was connected to a Spectrum4 amplifier (J&J Engineering, United States) interfacing with EEGer 4.3 neurofeedback software (EEG Spectrum Systems, CA). Separate ground and reference electrodes were placed on the right and left earlobes, respectively. Once all electrodes were connected, impedances were checked to be at or below 5kΩ measured at the Pz and reference electrode sites. Each session began with a 3-minute adjustment period where participants were allowed to become comfortable in the laboratory setting. This was followed by 15-minutes of continuous neurofeedback, where participants were asked to close their eyes for the duration of the training. For the purpose of NFB training specifically of the EEG-alpha rhythm, the raw EEG signal was band-pass filtered using the infinite impulse response function to extract the alpha (8-12Hz) amplitude with an epoch size of 0.5 seconds.

The protocol was such that participants were guided toward continually increasing or enhancing their absolute EEG-alpha amplitude beyond a moving threshold. The amplitude threshold for reward was calculated based on the moving average amplitude measured every 0.5 seconds. Thresholds in NFB are typically set in such a way that the participant achieves a certain level of success that is neither too high nor too low (Demos, 2005). As such, the initial threshold was set such that their EEG-alpha amplitude would temporarily exceed the moving threshold at random 65% of the time above the initial 1-minute average; by contrast, participants would fail to receive feedback 35% of the time. The rate of reward achieved by each participant was constantly monitored such that when participants achieved disproportionately larger (>90%) or lower (>30%) reward rates, the standard 65% reward ratio was re-calculated and applied. This ensured that participants were provided a relatively constant level of guidance (feedback) toward the target of increasing-enhancing their alpha amplitude relative to ongoing success toward that goal. Positive feedback was provided as a low frequency auditory tone; being that the sounding of the tone itself is not intrinsically rewarding, it must be assumed that participants are motivated by their own self-efficacy and/or the intrinsically rewarding properties of the targeted neurophysiological state (i.e., an increased 8-12 Hz amplitude within their EEG). Participants,

with their eyes closed, were not given explicit strategies for producing the tones, but were instead asked to focus their attention continuously toward the tones for guidance.

Sham Neurofeedback (NFB)

All set-up and training procedures applied to the sham NFB group were identical to those for the real EEG-Alpha NFB group. Instructions were similarly identical and all participants completed 15-minutes of sham NFB in which participants similarly attempted to produce the audio tones. However, whereas the real NFB group heard auditory feedback that validly reflected their own brain activity, the sham group heard a pre-recorded session that involved the exact same tones the real NFB group was exposed to (Raymond, et al 2005). Pre-recorded sessions were created by placing a digital voice recorder beside the computer speaker during Alpha-NFB training sessions, recording their auditory feedback tones. The pre-recorded session was then played back to Sham-NFB participants using Windows Media Player (Microsoft, USA). In this way, the feedback given to the sham group bore no relation to the participants' actual own brain activity, but still mimicked the feedback that would typically occur during a true NFB session.

2.4 Self-Report Measures

All self-report measures were administered online using the Qualtrics Research Suite (Qualtrics, Provo, UT) embedded within the University of Western Ontario Social Science website. Participants provided responses to the questionnaires via laptop computer in the presence of the experimenters during the experimental session. No identifying information was given by the participant during completions of surveys: instead an anonymous code was entered at the beginning of each survey.

Depression Anxiety Stress Scale (DASS-21)

The brief 21-item version of the Depression Anxiety Stress Scales (DASS; Lovibond & Lovibond, 1995) is a self-report measure of symptoms of depression, anxiety, and stress over the prior week. Participants indicated the extent to which they experienced each of the symptoms using a 4-point Likert-type scale between 0 ('Did not apply to me at all') and 3 ('Applied to me very much, or most of the time'). Example items for the *depression* subscale include "I couldn't

seem to experience any positive feelings at all" and "I found it difficult to work up the initiative to do things". Example items for the *anxiety* subscale include "I experienced trembling (e.g. in the hands)" and "I was worried about situations in which I might panic and make a fool of myself". Finally, example items for the *stress* subscale include "I found it hard to wind down" and "I tended to over-react to situations". The brief DASS-21 item version was developed by selecting the highest loading items from each scale of the original 42-item version of the DASS, while aiming to retain coverage of the full symptom content from each of the three mood states (Lovibond & Lovibond, 1995). The factor structure of the DASS-21 is stable, and its scales possess a good convergent and discriminate validity and excellent internal consistency in non-clinical samples (Antony et al., 1998). In terms of convergent validity, DASS-Depression and DASS-Anxiety have been found to be highly positively correlated with other measures of depression and anxiety, respectively (Antony et al., 1998; Brown et al., 1997). In terms of discriminant validity, the DASS performs as well as other self-report measures purporting to distinguish between depression and anxiety. The DASS-21 was used to detect potential group differences in depression, anxiety, and stress symptoms at baseline that may have been present despite group randomization.

Profile of Mood States (POMS-SF)

The Profile of Mood States-Short Form (POMS-SF; McNair et al., 1971; Curran et al, 1995) is a 37-item instrument that evaluates six transient distinct mood states: *depression, tension-anxiety, vigor-energy, fatigue, anger-hostility,* and *confusion-bewilderment*. Participants responded on a five-point Likert scale ranging from 0 ('not at all') to 4 ('extremely'). Items were single words such as "unhappy", "sad", "active", and "fatigued". The POMS-SF was derived from the original 65-item POMS, with several items from each POMS scale eliminated on the basis of their impact on subscale internal consistency and face validity. Subscale scores and a *total mood disturbance* (TMD) score are calculated, the latter a simply a sum of the 6 subscale scores with reverse scoring of the *vigor-energy* subscale. Cronbach's alpha values for internal consistency have ranged from 0.80 to 0.91 in the original development study (Curran et al, 1995). TMD and subscale scores from the POMS-SF were highly correlated with TMD and subscale scores using procedures from the full length POMS (all r's > .95). As such, the POMS-SF is an excellent alternative to the more time-consuming full-length POMS, presumably

retaining the construct validity properties strongly established for the latter instrument. The POMS-SF was administered both before and after each of the interventions to assess possible changes in mood states that occurred following the interventions.

Five Factor Mindfulness Questionnaire (FFMQ)

The FFMQ (Baer et al., 2006) was used to assess different aspects of mindfulness that are expected to be influenced by MM practice. It is currently the most frequently studied trait mindfulness questionnaire (Van Dam et al., 2009; Baer et al. 2008). A particular strength of the FFMQ is that it is based on a factor analysis of items from the five most widely used mindfulness questionnaires: the *Freiburg Mindfulness Inventory* (Buchheld et al., 2001), the *Mindful Attention Awareness Scale* (Brown & Ryan, 2003), the *Mindfulness Questionnaire* (Chadwick et al., 2005), the *Kentucky Inventory of Mindfulness Skills* (Baer et al.,2004), and the *Cognitive and Affective Mindfulness Scale* (Feldman et al., 2004). The FFMQ consists of 39 items that are rated on a 5-point Likert scale from 1 ('never or very rarely true') to 5 ('very often or always true'). Five subscales or "facets" are scored: (1) *Non-reactivity*, measuring the tendency to allow distracting thoughts, feelings and sensations to come and go, without getting caught up in them or carried away by them (an example is "Usually when I have distressing thoughts or images, I step back and am aware of the thought or image without getting take over by it"); (2) *Observing*, measuring the tendency to notice or attend to internal and external experiences, such as cognitions, emotions, physical sensations (e.g., "I pay attention to sounds, such as clocks ticking, birds chirping, or cars passing"); (3) *Describing*, measuring the tendency to describe and label experiences with words (e.g., "I'm good at finding words to describe my feelings"); (4) *Acting with Awareness*, measuring the ability to bring full awareness and undivided attention to current activity or experiences (e.g., "I rush through activities without being really attentive to them"); and (5) *Nonjudging*, referring to taking a nonevaluative stance toward inner experiences (e.g., "I tend to evaluate whether my perceptions are right or wrong"). Nineteen (19) negatively worded items are reverse scored, and the scores between 1 and 5 are summed to produce totals for each subscale as well as a total scale score reflecting the sum of the subscale scores (possible range: 39-195). Previous studies suggest that the five-factor structure of the FFMQ is robust across various samples, displaying adequate to good internal consistency with alpha values of 0.75 (Nonreactivity), 0.83 (Observing), 0.87 (Awareness), 0.87 (Nonjudging), and 0.91 (Describing)

in the development study. The FFMQ was given prior to intervention for baseline differences between groups to detect potential group differences in mindfulness-related traits at baseline that may have been present despite group randomization.

Toronto Mindfulness Scale (TMS)

Whereas most published mindfulness scales measure trait mindfulness, the TMS was designed to assess mindfulness as a state addressing a participant's experience during and immediately preceding a brief MM session (Lau, M. et al., 2006). The TMS measures the experience of mindfulness in terms of two components: (1) *decentering*, involving the self-regulation of attention that is focused on experiences in the present moment and differentiating an experiencing self from the content of experience as including thoughts, emotions, and sensations, and (2) *curiosity*, relating to experiences with an orientation of interest, openness, acceptance, and nonjudgment (Bishop et al., 2004). The TMS consists of 13 items that are rated on a 5-point Likert scale from 0 ('Not at all') to 4 ('Very much'). An example from the curiosity subscale is: "I was curious about each of the thoughts and feelings that I was having" and an example from the decentering subscale is: "I was more invested in just watching my experiences as they arose, than in figuring out what they could mean." Internal consistency reliability (coefficient alpha) for the subscales was 0.88 (Curiosity) and 0.84 (Decentring) in the development study, and construct validity was demonstrated by showing higher TMS factor scores immediately after mindfulness training. TMS was given to participants after their respective interventions to assess whether they differed regarding the degree to which they were associated with experiences of mindful decentering and mindful curiosity.

2.5 Behavioural Measures: Task Design and Stimuli

Stroop Test

The Stroop color-word task (Stroop, 1935) is an extensively studied paradigm in cognitive psychology for measuring attentional control. The task requires participants to name the colour of ink that a colour-word (e.g. BLUE) is present in. On certain trials, the words and the ink colour that they are written are congruent (e.g., the word BLUE written in blue ink),

whereas in others they are incongruent (e.g., the word BLUE written in red ink), and participants' task is to name the ink colour that words are written in, thereby overcoming a natural habit to read the words. A robust finding, referred to as the Stroop interference effect, involves an increase in the number of errors and time taken to respond to conditions where the semantic meaning of the word does not match the colour-ink (i.e., incongruent trials) in comparison with conditions involving matching semantic-visual information (i.e., congruent trials). Most cognitive theories posit that these behavioural effects arise due to competition for the allocation of attentional resources (Phaf et al., 1990) or conflict at the level of attentional control (selective and executive functioning; Dyer, 1973). In this study, the Stroop task was used as a measure of attentional control capacity, indicating a participant's ability to maintain task set (colour naming) and relatedly overcome automaticity effects involved in word reading.

Stimuli in the Stroop task were the four colour words "RED", "BLUE", "GREEN", and "YELLOW". These words were presented in the same colour-ink as the written word in congruent trials (e.g. RED presented in red ink) and in different colours for incongruent trials (e.g. RED presented in blue ink). The task was presented on a 21-inch CRT-monitor (100Hz vertical refresh rate, 1024 x 768 resolution) and running in the E-Prime 2.0 environment (Psychology Software Tools Inc., USA). Words were presented in Arial Font (font size 48pt), and viewed at a distance of approximately 70cm. Incongruent stimuli appeared in each of the three other colours with equal frequency, whereas the ratio of congruent to incongruent trials was 1:1. Participants were instructed to indicate the colour each word was presented in, while ignoring the semantic meaning of the word, as fast and as accurately as possible. Four keys on a standard QWERTY keyboard were used to enter their responses. The keys were colour coded using circular coloured stickers, with the key "s" for red, "c" for yellow, "m" for blue, and "l" for green. The keys were chosen to provide optimum comfort for the participant while responding with the index and middle finger of both hands. Stimuli were presented on the screen for 1500ms, followed by a variable inter-trial interval ranging between 1500 and 1800ms, where a centrally located fixation cross was presented. The stimulus word always appeared centrally on the screen, replacing the fixation cross.

The experiment began with a color-to-key acquisition phase which consisted of 48 trials presenting the four words but in black ink only (e.g. RED in black ink); completion of such trials resulted in all participants learning the key-colour associations with high speed and accuracy.

Indeed all participants were able to improve their overall accuracy and reaction time from the first 12 trials (accuracy: M=0.92, SD=0.16; reaction time: M=805.6ms, SD=286.4ms) to the last 12 trials (accuracy: M=0.95, SD=119.0; reaction time: M=585.8ms, SD=119.0ms). This was followed by a practice phase where 32 trials were presented to the participant which were identical to those used in the experimental blocks. During the acquisition and practice phases, response accuracy feedback was given following each trial. The experimental phase consisted of three blocks of 48 trials, for a total of 144 trials, with 72 congruent and 72 incongruent trials. The entire task lasted for approximately 8 minutes.

2.6 Electrophysiological Measures

Brain activity measured from EEG derives primarily from cortical pyramidal neurons lying directly under each surface electrode (Luck, 2005). When an excitatory neurotransmitter is released at the apical dendrites of a cortical pyramidal cell, current will flow from the extracellular space into the cell, yielding a net negativity outside the region of the apical dendrite. Current also flows out of the cell body and basal dendrites, yielding a net positivity in this area. Together, the negativity at the apical dendrites and positivity at the cell body create a tiny dipole. When thousands of spatially aligned dipoles summate within a region detectable under the electrode, the resulting voltage is then measured (Luck, 2005). As such, increases and decreases in voltage amplitude seen on an EEG signal would reflect the degree of synchrony and desynchrony within a local neuronal population, respectively.

EEG recordings have distinct advantages and disadvantages when used to make inferences about cognition. Measures derived from brain electrical activity have excellent temporal resolution in the millisecond domain (Davidson, 2000). This means neuronal activation is nearly instantaneously reflected in the EEG recording, making EEG measurements ideal for observing behaviors that have dynamic changes over short periods of time. For example, this is particularly useful when utilized in studies of the neural substrates of emotion or attention where the neural changes coincident with rapid phasic changes in behavioural state can be measured. The major disadvantage of EEG is its poor spatial resolution. This is due to large interelectrode

distance on a typical adult head as well as the highly resistive properties of the skull which distorts the spatial distribution of neuronal potentials (Davidson, 2000).

EEG Recording

The continuous EEG was recorded using a custom elastic cap and the ActiveTwo BioSemi amplifier system (BioSemi, Amsterdam, Netherlands). Cap sizes varied and were chosen based on participant head circumference. Recordings were taken from 32 Ag/AgCl electrodes following the international 10-20 system. Two electrodes were placed on the left and right mastoids. Electrooculogram generated from blinks and eye movements was recorded from 5 facial electrodes: two approximately 1cm above and below the participant's left eye, one on the nose bridge, one approximately 1cm to the left of the left eye, and one approximately 1cm to the right of the right eye. As per BioSemi's design, the ground electrode during acquisition was formed by the Common Mode Sense active electrode and the Driven Right Leg passive electrode (see www.biosemi.com/faq/cms&drl.htm for details). For further off-line analysis, the average reference was used. All bioelectric signals were digitally filtered at 0.1-100Hz (24dB/octave roll-off) and amplified on a laboratory computer using ActiView software (BioSemi), sampled at 512Hz and stored for offline analysis. Impedences were kept below 5kΩ. EEG recording occurred during the first pre-intervention three-minute baseline and continued through the study duration.

Data Reduction and Offline Analyses

Following EEG recording, all EEG data were preprocessed using routines available via EEGLab v12, an open source toolbox running in the MATLAB environment for electrophysiological signal processing (Delorme & Makeig, 2004; http://sccn.ucsd.edu/eeglab/). After being imported into MATLAB, the continuous EEG data were re-referenced using a common-average head reference algorithm, where an average of EEG activity at every electrode site is used as a reference, thereby removing noise common to all sites. Data were then digitally filtered depending on our experimental condition as will be described.

EEG Baseline Analyses

Baseline continuous EEG measurements taken before, during, and after the interventions were filtered with a low cutoff value of 1Hz and a high cutoff value of 30Hz using a finite

impulse response (FIR) filter. Continuous EEG data were then segmented into 1s epochs used for artifact rejection. We excluded epochs with abnormally large amplitudes (over ±75μV). Epochs contaminated by spurious gross-movement and other non-stereotyped artifacts were also identified by visual inspection and additionally rejected.

EEG Stroop Analyses

Event-related potentials (ERP) observed during Stroop performance were FIR filtered offline between 0.1Hz to 30Hz, 12dB/octave. ERP data were then segmented into a time window of -1000 to +800ms time-locked to Stroop stimulus onset, and baseline corrected using the pre-stimulus interval (-1000 to 0ms). ERP trials were calculated separately for congruent and incongruent Stroop trials, with only epochs containing correct responses used for further analyses (ERPs occurring during incorrect responses were rejected from further analysis). Independent component analysis (ICA) decomposition was used to remove stereotypical artifacts, because the Infomax algorithm has been shown to be reliable for separating ocular responses such as blinking and lateral eye movements (Jung et al., 2000). Epochs were also rejected based on abnormally large amplitudes (over ±75μV) and visual inspection of gross-movement artifacts.

Spectral Analysis for Continuous EEG at Baseline and During Intervention

EEG power was calculated by using Welch's power spectral density estimate in the Neurophysiological Biomarker Toolbox, an open source toolbox running in MATLAB (NBT; Hardstone et al., 2012; www.nbtwiki.net). Continuous EEG was Fast Fourier Transformed (FFT) and averaged in the frequency domain using a hamming window (1024 sampling points). The FFTs were then grouped into lower-alpha (8-10Hz), upper-alpha (10-12Hz), and overall alpha (8-12Hz) frequency bands and log-transformed. Average amplitude values in these bands were used for statistical analysis of absolute changes in spectral EEG during the pre- and post-intervention 3-minute baseline measurements. Amplitude measures during the 15-minute intervention itself were also calculated in five 3-minute segments.

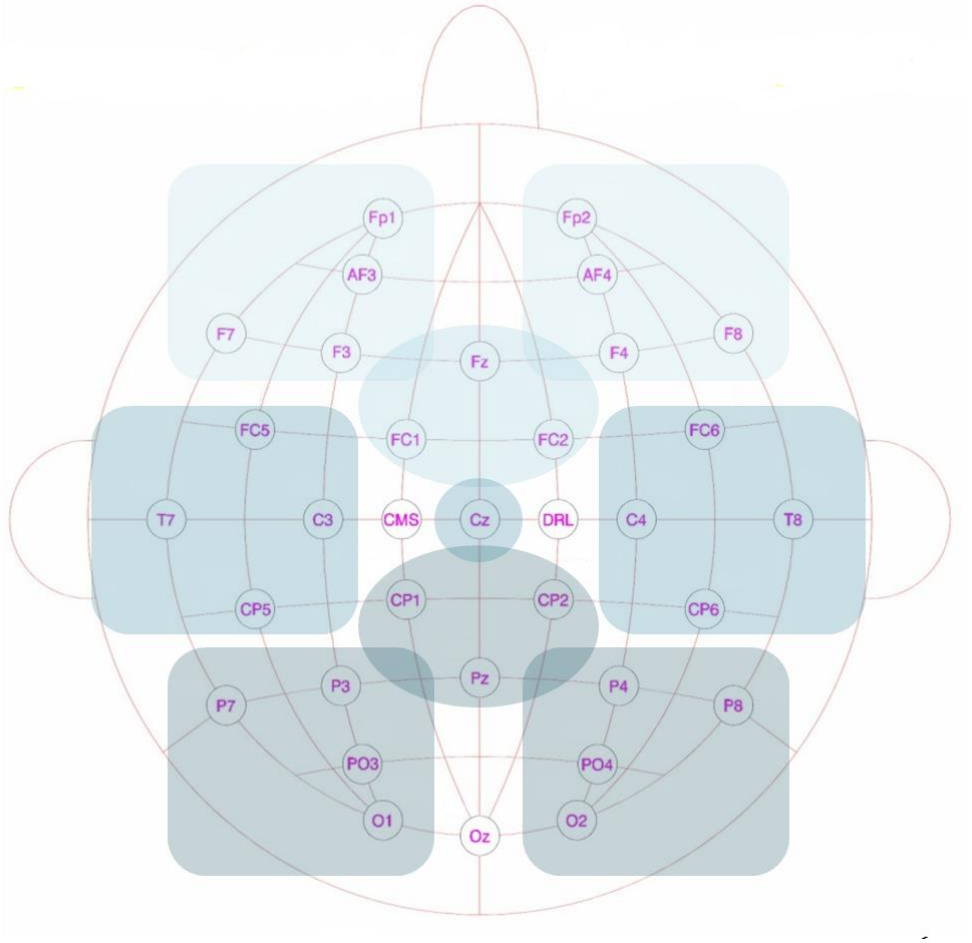
Following convention, the 32-channel EEG data were collapsed into nine clusters, resulting in regional means (see Figure 1): left frontal (Fp1, AF3, F7, F3), mid frontal (Fz, FC1, FC2), right frontal (Fp2, AF4, F8, F4), left central (T7, FC5, C3, CP5), mid-central (Cz), right central (T8, FC6, C4, CP6), left posterior (P7, P3, PO3, O1), mid-posterior (CP1, CP2, Pz), and

right posterior (P8, P4, PO4, O2). The average amplitude values across the respective electrode sites were calculated for these regional means for lower-alpha (8-10Hz), upper-alpha (10-12Hz), and overall alpha (8-12Hz) frequency bands as observed during each experimental condition. For statistical analyses, effects for *location* (left hemisphere [LH], midline, and right hemisphere [RH]) and *lobe* (frontal, central, posterior) were determined independently.

Event Related Desynchronization during Stroop Task

Event-related changes in the EEG-alpha band power were calculated using the ERD-method originally proposed by Pfurtscheller & Lopes da Silva (1999). Before calculating ERD, data were digitally band-pass filtered, squared (in order to obtain simple power estimates) and averaged separately between congruent vs. incongruent trials. ERD is defined as the percentage of a decrease (ERD; desynchronization) or increase (ERS; synchronization) in the band (alpha) power during a post-stimulus interval (A) as compared to a baseline reference interval (R): ERD/S% = (A – R)/R × 100%. As such, positive values reflected an increase in alpha power following stimulus presentation relative to pre-stimulus baseline, termed ERS, whereas negative values reflected a decrease in alpha power, in percentage units of the alpha power observed during the pre-stimulus baseline, termed ERD. The time window of -750ms to -250ms prior to stimulus onset was used as the baseline reference interval. Post-stimulus test intervals were two equivalent consecutive (short and late) time intervals between 200ms to 600ms post-stimulus onset (i.e., 200-400 and 400-600 msec). The 400-600ms time period was used as this usually pertains to the late negative ERP component that typically reflects the behavioural interference effect in the Stroop task and tends to correlate with behavioural performance (Liotti et al., 2000; Hanslmayr et al., 2008). Conversely the 200-400ms time period was aimed at observing the earlier aspects of stimulus processing that, in themselves, may not be a source of behavioural Stroop interference effect (Ilan and Polich, 1999). For statistical comparisons, data were collapsed into the lower alpha (8-10Hz) and upper alpha (10-12Hz) sub-bands. ERD values were measured separately for the 9 cortical regions as described above.

Figure 1: Topography of recorded EEG electrode positions, with shaded regions selected for statistical analyses



ERP Analysis for P300 Component during Stroop Task

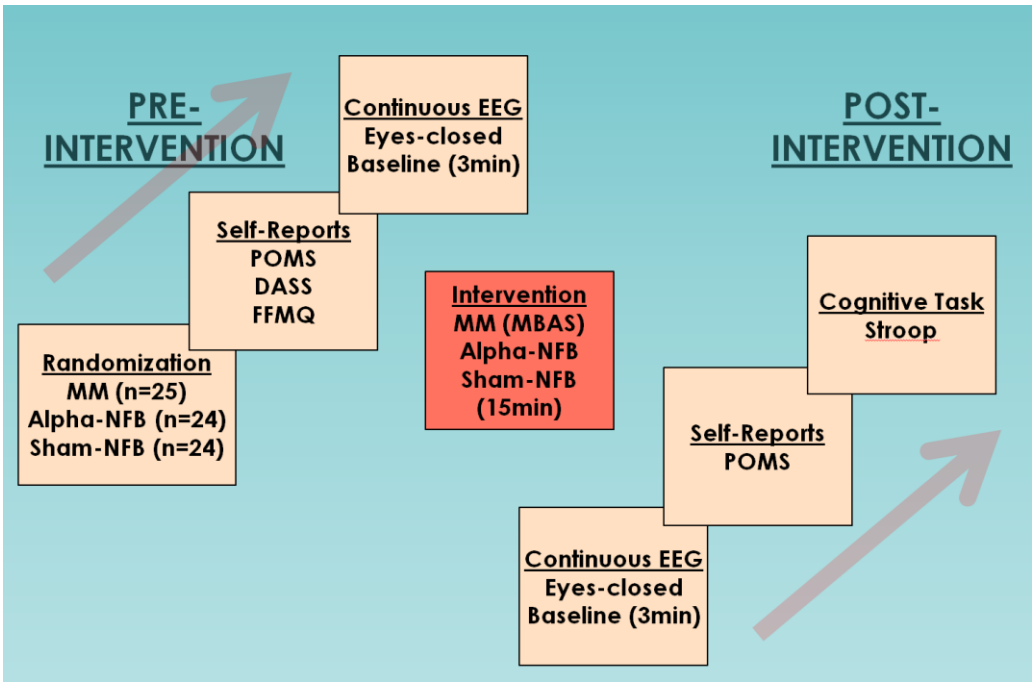
ERP analyses were conducted using the ERPLab, an open-source toolbox for processing event-related potential data within the MATLAB environment and tightly integrated with EEGLab (Lopez-Calderon & Luck, 2014; http://erpinfo.org/erplab). Artifact free epochs (-1000ms to 800ms post-stimulus) separated into congruent and incongruent trials were used for ERP analysis. The P300 component was defined as the largest positive peak within the time window of 300-600ms post stimulus onset, calculated using the ERPLab measurement tool. Amplitudes were evaluated using a mean area window of 50ms, built around the average peak amplitude for each condition. P300 amplitude at the Pz site was measured, as the P300 scalp distribution is typically characterized as the amplitude change over midline electrodes Fz, Cz,

and Pz (Johnson, 1993). The P300 response to target/non-target discrimination is typically largest at the midparietal (Pz) site, and specifically chosen as it indexes temporal-parietal P300 activity considered to reflect attentional resource allocation (Polich, 2010).

2.7 Procedure

A flow-chart of the study procedure in brief is depicted in Figure 2. Participants were randomly assigned to MM, EEG-Alpha NFB, or Sham-NFB. Pre-intervention baseline self-reports of DASS, POMS and FFMQ were administered via laptop computer following EEG electrode cap setup. The EEG cap was worn throughout the entire study, allowing for continuous EEG recording for all conditions. Additionally, participants in both the alpha-enhancement and sham NFB groups wore three additional electrodes at the Pz site, left, and right earlobes. A pre-intervention baseline EEG measurement was recorded for 3-minutes, where participants were asked to close their eyes and allow their minds to naturally wander. Each participant then underwent their respective interventions for 15-minutes. All interventions were conducted with eyes-closed and guided using standard published procedures by M.Sc. students Theodore Chow and Tanaz Javan as supervised by Dr. Paul Frewen. Participants in the MM group were also subjected to the MBAS with a meditation bell sounding at 3-minute intervals (3, 6, 9, 12, and 15-minute time points during the meditation). After each intervention, another 3-minute eyes closed post-intervention baseline EEG measurement was recorded. Participants then completed the POMS and TMS self-reports following the second baseline measurement. This was followed finally by the cognitive Stroop test and lasted for approximately 8-minutes. Following the Stroop task, participants completed a self-referential processing task (*Visual Verbal Self-Other Referential Processing Task*; VV-SORP-T; Frewen & Lundberg, 2013) that is the primary subject of another Master's thesis and therefore will not be described further here. Participants were finally debriefed at the conclusion of the study.

Figure 2: Flow-chart of study procedure



2.8 Statistical Analyses

Group-level statistical analyses were performed with IBM Statistics Package for the Social Sciences v.21 (SPSS). For all statistical analyses, whenever the sphericity assumption (equality of variances) had been violated (using Mauchly's test), Greenhouse-Geisser estimates of sphericity were employed to adjust the respective degrees of freedom.

Self-report measures

Group differences at baseline for last week depression, anxiety, and stress symptoms (DASS scores), trait mindfulness (FFMQ scores), and pre-intervention mood (POMS at baseline) were compared between groups. Group differences for intervention-associated state mindfulness (TMS scores) and post-intervention mood (POMS) were also compared. These measures were subjected to one-way independent measures ANOVA.

Behavioural Stroop Task

Stroop behavioural data were subjected to a two-way split-plot ANOVA with *Group* (MM, EEG-Alpha NFB, and Sham NFB) as a between-subjects factor and *Condition* (Congruent vs. Incongruent) as a within-subjects factor. Response times (RTs) and response accuracy served as the two dependent measures.

EEG-Alpha amplitude during continuous EEG baselines

Mean amplitude values for the lower (8-10Hz), upper (10-12Hz), and entire (8-12Hz) alpha frequency bands were analyzed separately, with each measure subjected to a four-way split-plot ANOVA with *Group* (MM, EEG-Alpha NFB, Sham NFB) as a between-subjects factor and *Time* (pre- and post-intervention), *Location* (LH, Midline, RH) and *Lobe* (Frontal, Central, Posterior) as within-subjects factors. Of particular interest were potential interaction effects that included the factors *Group* and *Time*, as this would indicate that the respective EEG-alpha amplitudes were influenced differentially by the three interventions.

EEG-Alpha amplitudes during Intervention

As per EEG measurements before and after therapy, mean absolute alpha amplitudes were calculated separately for the entire alpha frequency band (8-12Hz), as well as the upper (10-12Hz) and lower (8-10Hz) sub-bands. Amplitudes were subjected to a four-way split-plot ANOVA with *Group* (MM, EEG-Alpha NFB, and Sham-NFB) as a between-subject factor, and *Time* (first 0-3 minute period, second 4-6 minute period, third 7-9 minute period, fourth 10-12 minute period, and fifth 13-15 minute period), *Lobe* (Frontal, Central, Posterior), and *Location* (LH, Midline, RH) as within-subject factors. Like for the analysis of EEG-amplitude pre- and post-intervention, *Group* and *Time* interactions were of particular interest for investigating the ability of each intervention to uniquely modulate the alpha rhythm.

Event-related Desynchronization (ERD) during Stroop Task

Degree of ERD was calculated separately for the lower (8-10Hz) and upper (10-12Hz) alpha frequency sub-bands for both 200-400ms and 400-600ms post-stimulus test interval time windows. ERD data were subjected to a four-way split-plot ANOVA with *Group* (MM, EEG-Alpha NFB, Sham NFB) as a between-subjects factor and *Condition* (Congruent vs. Incongruent

trials), *Location* (LH, Midline, RH), and *Lobe* (Frontal, Central, Posterior) as within-subjects factors. However, even in the absence of effects observed involving *Condition* (congruent-vs-incongruent trials), given the explicit design of the Stroop task as involving congruent and incongruent conditions, planned comparisons were conducted for congruent and incongruent conditions separately.

Event-related Potentials (ERPs) during Stroop Task

Mean P300 amplitudes at the Pz site were subjected to a two-way split-plot ANOVA with *Group* (MM, EEG-Alpha NFB, and Sham-NFB) as a between-subjects factor and *Condition* (Congruent vs. Incongruent) as a within-subjects factor. However, even in the absence of effects involving *Condition* (congruent-vs-incongruent trials), again, given the explicit design of the Stroop task, planned comparisons were conducted for congruent and incongruent conditions separately.

Chapter 3 – Results

3.1 Group Differences at Baseline

Self-Reported Depression, Anxiety and Stress (DASS)

Data from baseline self-reports revealed that one participant (EEG-Alpha NFB group, Subject: 4693) had strong depressive scores on both the DASS and POMS (z-scores: 4.53 and 3.84, respectively). This participant was therefore excluded from subsequent post-intervention analyses. Two participants in the EEG-Alpha NFB group were also excluded from further analyses due to abnormally high (outlying) DASS-Depression scores (Subject: 2499, z-score = 3.18), and POMS-depression scores (Subject:7448, z-score = 3.70). Additionally, one participant (Subject: 1928) in the Sham-NFB did not complete the DASS survey. One participant in the EEG-Alpha NFB group (Subject: 5779) did not complete the FFMQ survey and was therefore excluded from analyses.

Table 1 reports group differences in self-reported depression, anxiety, stress, and trait mindfulness at baseline. Referring to depression, anxiety and stress symptoms, unfortunately, despite randomization to groups and removal of outlying scores, significant differences pre-intervention were found for DASS-Anxiety scores, $F(2, 69) = 3.52$, $p = 0.035$, and there was a similar trend for DASS-Stress scores, $F(2, 69) = 2.57$, $p = 0.084$. Post-hoc comparisons using the Tukey HSD test indicated that the MM group reported significantly less anxiety, $t(47) = 2.5$, $p = 0.015$, and less stress, $t(47) = 2.0$, $p = 0.05$, over the week preceding testing than did the EEG-Alpha NFB group, and a trend towards less stress over the week preceding testing when compared with the Sham NFB group, $t(46) = -1.8$, $p = 0.07$. However, no significant correlations were found between the DASS-Anxiety and EEG measures. As such, DASS-Anxiety scores were not included as a covariate in these analyses. However, DASS-Anxiety did correlate significantly with behavioural Stroop accuracy/reaction times observed during the incongruent condition, and with self-report measures of state mindfulness (TMS) and mood (all POMS subscales). As such, DASS-Anxiety scores were used as a covariate to partly account for differences between groups observed on the TMS and POMS.

Self-Reported Trait Mindfulness (FFMQ)

Referring to total FFMQ scores, a significant correlation was found between the DASS-Anxiety and FFMQ-Observe, FFMQ-Nonjudge, and FFMQ-Total measures. As such, DASS-Anxiety scores were included as a covariate when comparing group differences between these FFMQ subscales only. No significant differences were found for the FFMQ-Total score between the three intervention groups at baseline, $F(2,67) = 0.11$, $p = 0.90$. However, significant pre-intervention differences were found for the FFMQ-Describe subscale, despite randomization to groups. Post-hoc comparisons using Tukey HSD revealed FFMQ-Describe scores for the MM group were significantly higher than those reported by the EEG-Alpha NFB group, while neither the MM nor EEG-Alpha NFB group differed significantly from the Sham-NFB group.

Table 1: Group Differences in Self-Reported Depression, Anxiety, Stress, and Trait Mindfulness

Measure	EEG-Alpha NFB		MM		Sham-NFB		Statistical values
	M	SD	M	SD	M	SD	
DASS-Depression	3.09	2.8	2.28	2.2	3.26	3.4	$F(2, 67) = 0.84$, $p = 0.43$
DASS-Anxiety	5.38	3.9	3.00	2.7	3.56	3.1	$F(2, 69) = 3.52$, $p = 0.035$
DASS-Stress	7.33	4.0	5.08	3.9	7.04	3.4	$F(2, 69) = 2.57$, $p = 0.084$
FFMQ-Observe	26.34	4.9	24.88	5.0	25.29	4.1	$F(2, 67) = 0.16$, $p = 0.85$
FFMQ-Describe	24.78	5.3	28.84	5.4	26.12	4.9	$F(2, 69) = 3.81$, $p = 0.027$
FFMQ-Awareness	24.61	6.1	24.6	5.3	26.12	5.3	$F(2, 69) = 0.60$, $p = 0.55$
FFMQ-Non-reactivity	20.87	2.9	20.96	5.3	21.25	3.4	$F(2, 69) = 0.058$, $p = 0.94$
FFMQ-Non-judging	24.47	6.8	26.64	6.5	25.46	6.2	$F(2, 67) = 0.085$, $p = 0.92$
FFMQ-Total	121.1	13.3	125.9	16.7	124.2	15.8	$F(2, 67) = 0.11$, $p = 0.90$

3.2 Effects of Intervention on Self-Reported Mood (Profile of Mood States; POMS) and State Mindfulness (Toronto Mindfulness Scale; TMS)

The POMS was completed both before and after the interventions, whereas the TMS was completed only after the interventions. Therefore, scores from the two surveys were analysed separately, with POMS using a split-plot ANOVA for each subscale and the TMS analyzed via between-groups ANOVA. Table 2 displays group differences in both POMS and TMS scores. Two participants in the EEG-Alpha NFB group (Subject ID: 4693 and 7448) were excluded from analyses at baseline due to outlying scores (z-scores on the POMS-Depression subscale, Subject: 4693, z-score=3.84; Subject: 7448, z-score=3.70; POMS-Anger subscale, Subject: 7448, z-

score=4.80; and POMS-Total Mood Disturbance scale, Subject: 7448, z-score=4.90). One participant in the EEG-Alpha NFB group (Subject: 5779) did not complete the POMS survey and was excluded from further analyses accordingly. In addition, a total of five participants were excluded from post-intervention analyses due to their omitting responses (Alpha-Up NFB, Subject: 5779, 2195; MM, Subject: 7756; Sham-NFB, Subject: 6658, 7258, 7693).

Referring to POMS scores, a 2 (Time: Pre/Post) × 3 (Group) ANOVA found a significant main effect of Time for total mood disturbance (TMD), $F(1,60) = 6.75$, $p = 0.012$, $\eta^2 = 0.101$, as well as for the specific POMS subscales of vigor, $F(1,60) = 6.7$, $p = 0.012$, $\eta^2 = 0.100$, anger, $F(1,60) = 13.48$, $p = 0.001$, $\eta^2 = 0.183$, tension, $F(1,60) = 10.28$, $p = 0.002$, $\eta^2 = 0.146$, and confusion, $F(1,60) = 8.61$, $p = 0.005$, $\eta^2 = 0.126$. Main effects of Time were not found in depression and fatigue subscales. No significant main effects of Group were found for any of the subscales post-intervention, and we further confirmed that there were no significant differences between groups on the POMS-Total Mood Disturbance or for any of the POMS subscales at baseline.

However, a significant interaction between Group and Time was found for the confusion subscale, $F(2,60) = 3.91$, $p = 0.025$, $\eta^2 = 0.115$. At post-intervention, the Sham-NFB group had reported being significantly less confused than the Alpha-NFB group, $t(39) = 2.4$, $p = 0.02$; other group comparisons were non-significant. In addition, within-group pairwise comparisons revealed that pre-intervention confusion subscale scores significantly decreased for the Sham-NFB group, $t(20) = 4.2$, $p < 0.001$, and the MM group, $t(23) = 2.8$, $p = 0.01$, but not for the EEG-alpha group, $t(19) = 1.3$, $p = 0.22$.

Referring to TMS scores, a total of five individuals were excluded from post-intervention analyses due to participants omitting responses after intervention (Alpha-Up NFB, Subject: 5779, 2195; MM, Subject: 6630, 7756; Sham-NFB, Subject: 2968). After removal of outliers, Table 2 also shows that no significant differences between groups were observed for the TMS curiosity subscale, $F(2,64) = 0.889$, $p = 0.42$, or the TMS decentering subscale, $F(2,64) = 0.44$, $p = 0.65$.

Table 2: Group Differences in Self-Reported Mood Pre-vs-Post Intervention

Survey	POMS Scores, Mean (SD)		Group F(2, 60) (η^2)	Time F(1, 60) (η^2)	Interaction F(2,60) (η^2)
	Before	After			
POMS-Depression			0.155 (0.005), p=0.86	3.53 (0.056), p=0.065	1.75 (0.055), p=0.18
Alpha NFB	5.3 (4.8)	4.0 (4.3)			
MM	4.2 (3.3)	3.2 (3.3)			
Sham NFB	6.0 (6.0)	3.1 (4.0)			
POMS-Vigor			0.318 (0.011), p=0.73	6.70 (0.100), p=0.012*	1.61 (0.051), p=0.21
Alpha NFB	10.0 (3.5)	9.2 (4.6)			
MM	12.2 (4.2)	9.6 (5.4)			
Sham NFB	11.8 (4.4)	9.1 (5.7)			
POMS-Anger			0.243 (0.008), p=0.78	13.48 (0.183), p=0.001**	0.668 (0.022), p=0.52
Alpha NFB	5.8 (4.1)	4.1 (5.2)			
MM	4.4 (3.1)	3.1 (3.4)			
Sham NFB	5.0 (3.1)	2.6 (3.3)			
POMS-Tension			0.346 (0.011), p=0.71	10.28 (0.146), p=0.002**	1.60 (0.051), p=0.21
Alpha NFB	9.4 (4.9)	6.8 (4.7)			
MM	8.0 (4.9)	5.3 (4.3)			
Sham NFB	8.6 (4.8)	4.2 (4.0)			
POMS-Confusion			0.499 (0.016), p=0.61	8.61 (0.126), p=0.005**	3.91 (0.115), p=0.025*
Alpha NFB	6.8 (2.6)	6.1 (3.0)			
MM	6.2 (3.6)	4.6 (3.4)			
Sham NFB	6.7 (3.8)	3.6 (3.2)			
POMS-Fatigue			0.171 (0.006), p=0.84	3.75 (0.059), p=0.058	0.368 (0.012), p=0.694
Alpha NFB	7.1 (4.1)	6.0 (4.2)			
MM	6.4 (4.1)	5.4 (3.9)			
Sham NFB	7.4 (4.0)	5.6 (3.8)			
POMS-TMD			0.149 (0.005), p=0.86	6.75 (0.101), p=0.012*	1.55 (0.049), p=0.22
Alpha NFB	24.3 (17.6)	17.7 (18.0)			
MM	17.0 (18.0)	12.1 (16.8)			
Sham NFB	21.8 (19.7)	10.0 (14.2)			
TMS-Curiosity	---		F(2, 64) = 0.889, p = 0.42	---	---
Alpha NFB	---	13.67 (5.9)			
MM	---	13.13 (5.6)			
Sham NFB	---	15.13 (4.1)			
TMS-Decentering	---		F(2, 64) = 0.440, p = 0.65	---	---
Alpha NFB	---	13.43 (5.0)			
MM	---	12.52 (4.1)			
Sham NFB	---	13.74 (4.6)			

POMS-subscale and TMS-subscale scores before and after intervention, reported as Means (SD)

3.3 Effects of Intervention on EEG Baselines

Participants were included in analyses of EEG baselines if they retained >40% of the 1-second epochs of their total 3-minute EEG recordings pre- and post-intervention after artifact rejection and EEG pre-processing. As such, two participants were excluded, one from the EEG-Alpha NFB group (Subject: 8708, 24.4% retained at pre-intervention, 28.9% retained at post-intervention) and one from the MM group (Subject: 7756, 30.0% at pre-intervention, 27.8% at post-intervention).Tables 3, 4, and 5 report the results for EEG alpha amplitudes before-vs-after

the three interventions as analyzed using a split-plot ANOVA (Tables 3, 4, and 5 reports results for the full [8-12 Hz], lower [8-10 Hz], and upper [10-12 Hz] alpha bands, respectively).

Full (8-12 Hz) Alpha Band

As shown in Table 3, referring to the full alpha band (8-12 Hz), only a main effect of *Location* was found, with post-hoc tests indicating that alpha amplitudes were higher in the left hemisphere, $t(61) = 10.5$, $p < 0.001$, and right hemisphere, $t(61) = -10.9$, $p < 0.001$, relative to the midline. Despite the lack of *Group* effects, planned comparisons within each group for their ability to manipulate the alpha rhythm (i.e., effect of *Time*, pre-post) were performed using pairwise t-tests. Whereas neither of the active MM and EEG-Alpha NFB interventions produced significant within-group changes in EEG-Alpha amplitude pre-vs. post-intervention, the Sham-NFB group revealed significant *decreases* in EEG-Alpha amplitude at the right-frontal, $t(20) = 2.7$, $p = 0.01$, and mid-posterior regions, $t(20) = 2.2$, $p = 0.04$.

Table 3: Group differences in full-band EEG alpha amplitudes (8-12 Hz) pre-vs-post intervention

EEG Scalp Regions	EEG-Alpha NFB		MM		Sham-NFB	
	Before	After	Before	After	Before	After
Left Frontal	0.302 (0.098)	0.285 (0.094)	0.367 (0.228)	0.399 (0.256)	0.348 (0.161)	0.322 (0.154)
Mid Frontal	0.204 (0.042)	0.198 (0.034)	0.220 (0.040)	0.229 (0.046)	0.221 (0.046)	0.213 (0.040)
Right Frontal	0.289 (0.076)	0.278 (0.069)	0.367 (0.162)	0.416 (0.219)	0.391 (0.189)	0.319 (0.127)
Left Central	0.311 (0.192)	0.282 (0.108)	0.309 (0.139)	0.315 (0.110)	0.355 (0.185)	0.306 (0.132)
Mid Central	0.207 (0.048)	0.196 (0.041)	0.223 (0.049)	0.222 (0.050)	0.216 (0.042)	0.207 (0.045)
Right Central	0.286 (0.138)	0.319 (0.188)	0.321 (0.121)	0.357 (0.171)	0.346 (0.166)	0.320 (0.178)
Left Posterior	0.298 (0.063)	0.309 (0.097)	0.340 (0.135)	0.328 (0.119)	0.367 (0.121)	0.357 (0.097)
Mid Posterior	0.202 (0.041)	0.195 (0.031)	0.218 (0.046)	0.214 (0.042)	0.217 (0.043)	0.203 (0.035)
Right Posterior	0.310 (0.097)	0.321 (0.092)	0.322 (0.099)	0.333 (0.124)	0.351 (0.121)	0.333 (0.127)

EEG-Alpha, 8-12Hz, reported as Means (SD)

Main and Interaction Effects	Statistics
Group	$F(2, 59) = 1.697$, $\eta^2 = 0.054$, $p = 0.192$
Time	$F(1, 59) = 0.248$, $\eta^2 = 0.004$, $p = 0.620$
Time × Group	$F(2, 59) = 1.657$, $\eta^2 = 0.053$, $p = 0.199$
Hemisphere	$F(2, 118) = 87.56$, $\eta^2 = 0.597$, $p < 0.001$**
Hemisphere × Group	$F(4, 118) = 0.579$, $\eta^2 = 0.019$, $p = 0.651$
Lobe	$F(2, 118) = 0.708$, $\eta^2 = 0.012$, $p = 0.460$
Lobe × Group	$F(4, 118) = 1.171$, $\eta^2 = 0.038$, $p = 0.326$
Time × Hemisphere	$F(2, 118) = 0.912$, $\eta^2 = 0.015$, $p = 0.388$
Time × Hemisphere × Group	$F(4, 118) = 1.634$, $\eta^2 = 0.052$, $p = 0.182$
Time × Lobe	$F(2, 118) = 0.017$, $\eta^2 = 0.000$, $p = 0.979$
Time × Lobe × Group	$F(4, 118) = 1.332$, $\eta^2 = 0.043$, $p = 0.264$
Hemisphere × Lobe	$F(4, 236) = 0.583$, $\eta^2 = 0.010$, $p = 0.616$
Hemisphere × Lobe × Group	$F(8, 236) = 0.937$, $\eta^2 = 0.031$, $p = 0.466$
Time × Hemisphere × Lobe	$F(4, 236) = 1.747$, $\eta^2 = 0.029$, $p = 0.159$
Time × Hemisphere × Lobe × Group	$F(8, 236) = 0.825$, $\eta^2 = 0.027$, $p = 0.552$

EEG-Alpha, 8-12Hz, Mixed Between Within ANOVA Statistics

Lower (8-10 Hz) Alpha Band

As shown in Table 4, referring to the lower alpha band (8-10 Hz), main effects of *Time*, *Lobe*, and *Hemisphere* were subsumed under a significant 3-way interaction. However, no significant main effect or interaction involving *Group* was observed. Further analysis of the 3-way *Time* × *Lobe* × *Hemisphere* interaction was therefore conducted across groups. Post-hoc results indicated there was an overall *decrease* in lower alpha-band amplitude specifically within the posterior regions (left-posterior, mid-posterior and right-posterior) pre-vs-post intervention. Thus the left-posterior amplitude decreased from pre-intervention (M=2.78, SD=1.1) to post-intervention (M=2.60, SD=1.1), $t(60) = 3.3$, $p = 0.002$, the mid-posterior amplitude decreased from pre-intervention (M=1.75, SD=0.7) to post-intervention (M=1.67, SD=0.7), $t(60) = 2.2$, $p = 0.03$, and the right-posterior amplitude decreased with borderline significance from pre-intervention (M=2.90, SD=1.2) to post-intervention (M=2.78, SD=1.2), $t(60) = 1.9$, $p = 0.06$.

Despite the lack of *Group* effects, planned comparisons between groups for their ability to manipulate the lower alpha rhythm revealed that these decreases in amplitude were seen specifically in the Alpha-NFB and MM group, but not in the Sham-NFB group. The EEG-Alpha NFB group had significant decreases in EEG-alpha amplitude from before intervention (M = 1.73, SD = 0.74) to after intervention (M = 1.58, SD = 0.67) at the mid-posterior region, where the NFB training site was located, $t(16) = 2.89$, $p = 0.011$. A similar significant decrease in EEG-alpha amplitude at the left-posterior region was seen in the MM group, from before (M=2.73, SD = 1.14) to after intervention (M = 2.54, SD = 1.11), $t(23) = 2.45$, $p = 0.022$. Across the two active intervention groups (MM and NFB), significant amplitude differences were seen pre-vs. post-intervention in the left-frontal, $t(40) = 2.1$, $p = 0.04$, left-posterior, $t(40) = 3.1$, $p = 0.003$, and mid-posterior regions, $t(40) = 2.6$, $p = 0.01$, and marginally significant results were also observed at the right-posterior region, $t(40) = 1.9$, $p = 0.06$. In all regions, EEG-Alpha amplitude *decreased* at post-intervention. No significant differences in any of the scalp regions were seen after Sham-NFB therapy.

Table 4: Group differences in lower-band EEG alpha amplitudes (8-10 Hz) pre-vs-post intervention

EEG Scalp Regions	EEG-Alpha NFB		MM		Sham-NFB	
	Before	After	Before	After	Before	After
Left Frontal	1.552 (0.566)	1.498 (0.561)	1.510 (0.542)	1.452 (0.508)	1.707 (0.600)	1.681 (0.679)
Mid Frontal	1.372 (0.500)	1.354 (0.515)	1.445 (0.527)	1.401 (0.527)	1.593 (0.546)	1.561 (0.613)
Right Frontal	1.548 (0.538)	1.515 (0.535)	1.558 (0.588)	1.506 (0.547)	1.696 (0.609)	1.635 (0.660)
Left Central	1.371 (0.506)	1.329 (0.488)	1.365 (0.482)	1.339 (0.469)	1.453 (0.520)	1.440 (0.532)
Mid Central	1.277 (0.476)	1.190 (0.481)	1.382 (0.462)	1.328 (0.465)	1.477 (0.564)	1.484 (0.625)
Right Central	1.483 (0.558)	1.469 (0.513)	1.465 (0.512)	1.421 (0.491)	1.485 (0.547)	1.478 (0.606)
Left Posterior	2.637 (1.197)	2.492 (1.144)	2.728 (1.140)	2.548 (1.110)	2.951 (1.125)	2.744 (1.095)
Mid Posterior	1.734 (0.740)	1.584 (0.672)	1.730 (0.768)	1.645 (0.708)	1.776 (0.753)	1.763 (0.817)
Right Posterior	2.792 (1.227)	2.689 (1.192)	2.786 (1.264)	2.649 (1.183)	3.109 (1.305)	3.015 (1.367)

Lower EEG-Alpha, 8-10Hz, reported as Means (SD)

Main Effects and Interactions	Statistics
Group	$F(2, 58) = 0.410$, $\eta^2 = 0.014$, $p = 0.666$
Time	$F(1, 58) = 4.231$, $\eta^2 = 0.068$, $p = 0.044$*
Time × Group	$F(2, 58) = 0.067$, $\eta^2 = 0.002$, $p = 0.936$
Hemisphere	$F(2, 116) = 118.47$, $\eta^2 = 0.671$, $p < 0.001$**
Hemisphere × Group	$F(4, 116) = 0.384$, $\eta^2 = 0.013$, $p = 0.765$
Lobe	$F(2, 116) = 189.27$, $\eta^2 = 0.768$, $p < 0.001$**
Lobe × Group	$F(4, 116) = 0.284$, $\eta^2 = 0.010$, $p = 0.786$
Time × Hemisphere	$F(2, 116) = 2.280$, $\eta^2 = 0.038$, $p = 0.123$
Time × Hemisphere × Group	$F(4, 116) = 1.410$, $\eta^2 = 0.046$, $p = 0.246$
Time × Lobe	$F(2, 116) = 9.380$, $\eta^2 = 0.139$, $p = 0.001$*
Time × Lobe × Group	$F(4, 116) = 0.170$, $\eta^2 = 0.006$, $p = 0.893$
Hemisphere × Lobe	$F(4, 232) = 94.77$, $\eta^2 = 0.620$, $p < 0.001$**
Hemisphere × Lobe × Group	$F(8, 232) = 1.268$, $\eta^2 = 0.042$, $p = 0.286$
Time × Hemisphere × Lobe	$F(4, 232) = 3.813$, $\eta^2 = 0.062$, $p = 0.024$*
Time × Hemisphere × Lobe × Group	$F(8, 232) = 1.301$, $\eta^2 = 0.043$, $p = 0.273$

Lower EEG-Alpha, 8-10Hz, Mixed Between Within ANOVA Statistics

Upper (10-12 Hz) Alpha Band

Finally, as shown in Table 5, referring to the upper alpha band (10-12 Hz), main effects of *Lobe* and *Hemisphere* were subsumed under a significant 2-way interaction. Again, no significant main effect or interaction involving *Group* was observed. The *Lobe* × *Hemisphere* interaction was therefore examined across groups. Across pre-post measurements, post-hoc comparisons indicated that alpha amplitudes across all nine scalp regions were significantly different, except between left-posterior and right posterior, $t(61) = -0.28$, $p = 0.78$, left-frontal and right-frontal, $t(61) = -1.7$, $p = 0.09$, and left-frontal and right-central, $t(61) = 0.69$, $p = 0.49$.

Similar to the other alpha subbands, pairwise t-tests were performed within each group to observe potential within-group changes in EEG-Alpha pre-vs. post-intervention. Whereas no significant change in EEG-Alpha amplitude was seen in the non-active Sham-NFB control, combining the two active intervention groups (MM and NFB) showed a significant decrease in EEG-Alpha amplitude in the mid-posterior region where training occurred for the NFB group, $t(40) = 2.3$, $p = 0.03$.

Table 5: Group differences in upper-band EEG alpha amplitudes (10-12 Hz) pre-vs-post intervention

EEG Scalp Regions	EEG-Alpha NFB		MM		Sham-NFB	
	Before	After	Before	After	Before	After
Left Frontal	0.527 (0.111)	0.523 (0.099)	0.589 (0.192)	0.604 (0.228)	0.590 (0.159)	0.570 (0.163)
Mid Frontal	0.468 (0.109)	0.460 (0.123)	0.495 (0.118)	0.493 (0.120)	0.507 (0.141)	0.511 (0.134)
Right Frontal	0.531 (0.101)	0.529 (0.095)	0.606 (0.155)	0.630 (0.199)	0.626 (0.175)	0.579 (0.139)
Left Central	0.514 (0.152)	0.495 (0.075)	0.537 (0.107)	0.527 (0.108)	0.585 (0.184)	0.551 (0.159)
Mid Central	0.445 (0.110)	0.432 (0.125)	0.474 (0.120)	0.469 (0.127)	0.470 (0.145)	0.477 (0.149)
Right Central	0.515 (0.130)	0.543 (0.133)	0.565 (0.121)	0.576 (0.123)	0.578 (0.140)	0.564 (0.145)
Left Posterior	0.687 (0.151)	0.676 (0.131)	0.740 (0.208)	0.717 (0.120)	0.771 (0.190)	0.759 (0.180)
Mid Posterior	0.459 (0.114)	0.445 (0.100)	0.497 (0.126)	0.483 (0.121)	0.486 (0.122)	0.484 (0.126)
Right Posterior	0.709 (0.168)	0.696 (0.128)	0.732 (0.186)	0.716 (0.168)	0.764 (0.186)	0.758 (0.192)

Upper EEG-Alpha, 10-12Hz, reported as Means (SD)

Main Effects and Interactions	Statistics
Group	$F(2, 59) = 1.103$, $\eta^2 = 0.036$, $p = 0.338$
Time	$F(1, 59) = 1.184$, $\eta^2 = 0.020$, $p = 0.281$
Time × Group	$F(2, 59) = 0.266$, $\eta^2 = 0.009$, $p = 0.767$
Hemisphere	$F(2, 118) = 173.6$, $\eta^2 = 0.746$, $p < 0.001$**
Hemisphere × Group	$F(4, 118) = 0.482$, $\eta^2 = 0.016$, $p = 0.720$
Lobe	$F(2, 118) = 54.21$, $\eta^2 = 0.479$, $p < 0.001$**
Lobe × Group	$F(4, 118) = 0.383$, $\eta^2 = 0.013$, $p = 0.759$
Time × Hemisphere	$F(2, 118) = 0.847$, $\eta^2 = 0.014$, $p = 0.406$
Time × Hemisphere × Group	$F(4, 118) = 1.567$, $\eta^2 = 0.050$, $p = 0.202$
Time × Lobe	$F(2, 118) = 0.547$, $\eta^2 = 0.009$, $p = 0.580$
Time × Lobe × Group	$F(4, 118) = 1.219$, $\eta^2 = 0.040$, $p = 0.306$
Hemisphere × Lobe	$F(4, 236) = 48.74$, $\eta^2 = 0.452$, $p < 0.001$**
Hemisphere × Lobe × Group	$F(8, 236) = 1.104$, $\eta^2 = 0.036$, $p = 0.361$
Time × Hemisphere × Lobe	$F(4, 236) = 1.856$, $\eta^2 = 0.031$, $p = 0.131$
Time × Hemisphere × Lobe × Group	$F(8, 236) = 1.095$, $\eta^2 = 0.036$, $p = 0.368$

EEG Change During Intervention

Participants were only included in final analyses of EEG change during the interventions if they retained >60% of their total 15-minute data during the intervention period after artifact rejection and EEG pre-processing. One participant in the Sham-NFB group (Subject: 7258) was removed due to retaining only 11.1% and 55.6% of their data during the fourth and fifth segments of the intervention. Additionally, one participant in the EEG-Alpha NFB group (Subject: 8073) was excluded due to excessive movement artifacts causing EEG data loss.

Tables 6, 7, and 8 report the results for EEG alpha amplitudes during the 15-minute intervention, divided into five separate time windows, each three minutes in duration (Tables 6, 7, and 8 reports results for the split-plot ANOVA of the full, lower, and upper alpha bands, respectively). Main effects and interactions involving *Time, Lobe,* and *Hemisphere* were found for the full (8-12 Hz), lower (8-10 Hz) and upper (10-12 Hz) alpha bands. Whereas no main effect or interactions involving *Group* were found for the full EEG-alpha band, a 4-way interaction with *Time, Lobe* and *Hemisphere* was statistically significant for the lower (8-10Hz) alpha band ($p = 0.028$, $\eta^2 = 0.065$), and marginally significant for the upper (10-12 Hz) alpha band ($p = 0.067$, $\eta^2 = 0.050$).

Full Alpha Band (8-12 Hz)

Despite the lack of main effects or interactions involving *Group* for the 8-12 Hz alpha band, planned comparisons across the intervention groups were conducted (Figure 3). The Alpha-NFB group was able to significantly *increase* their 8-12Hz alpha rhythm across the whole posterior region (left-posterior, mid-posterior, and right-posterior). A one-way repeated ANOVA revealed significant 8-12Hz amplitude changes in the left-posterior, $F(4,68) = 3.8$, $p = 0.029$, $\eta^2 = 0.181$, mid-posterior, $F(4,68) = 4.9$, $p = 0.01$, $\eta^2 = 0.223$, and right-posterior regions, $F(4,68) = 3.9$, $p = 0.016$, $\eta^2 = 0.189$. Subsequent pairwise t-tests revealed that these significant changes typically occurred in the final periods of the intervention, typically after the 10-12minute period.

The MM group was also able to significantly *increase* their 8-12Hz alpha rhythm, but only in the frontal region (left-, mid-, and right-frontal). A one-way repeated ANOVA revealed significant 8-12Hz amplitude changes in the mid-frontal, $F(4,96) = 3.0$, $p = 0.05$, $\eta^2 = 0.109$, and borderline significant changes in the left-frontal, $F(4,96) = 2.5$, $p = 0.08$, $\eta^2 = 0.095$, and right-

frontal regions, $F(4,96) = 2.8$, $p = 0.07$, $\eta^2 = 0.105$. Similar to Alpha-NFB, pairwise t-tests revealed these changes typically occurred toward the end of the intervention, after the 10-12 minute period.

In summary, whereas significant *decreases* in amplitudes of the lower and upper alpha bands were observed within the two active interventions, significant *increases* were observed for the full (8-12 Hz) band. Finally, as opposed to the active interventions (Alpha-NFB and MM groups), the Sham-NFB group showed *decreases* in their 8-12Hz amplitude specific to the mid-posterior region, $F(4,80) = 3.5$, $p = 0.025$, $\eta^2 = 0.148$. Pairwise t-tests revealed that this change occurred immediately after the first 3-minute period of the intervention.

Figure 3: Within group differences in full-band EEG alpha amplitudes (8-12Hz) during 15-minute intervention across frontal and posterior sites

* indicates $p < 0.05$ (using within-group paired student t-tests)

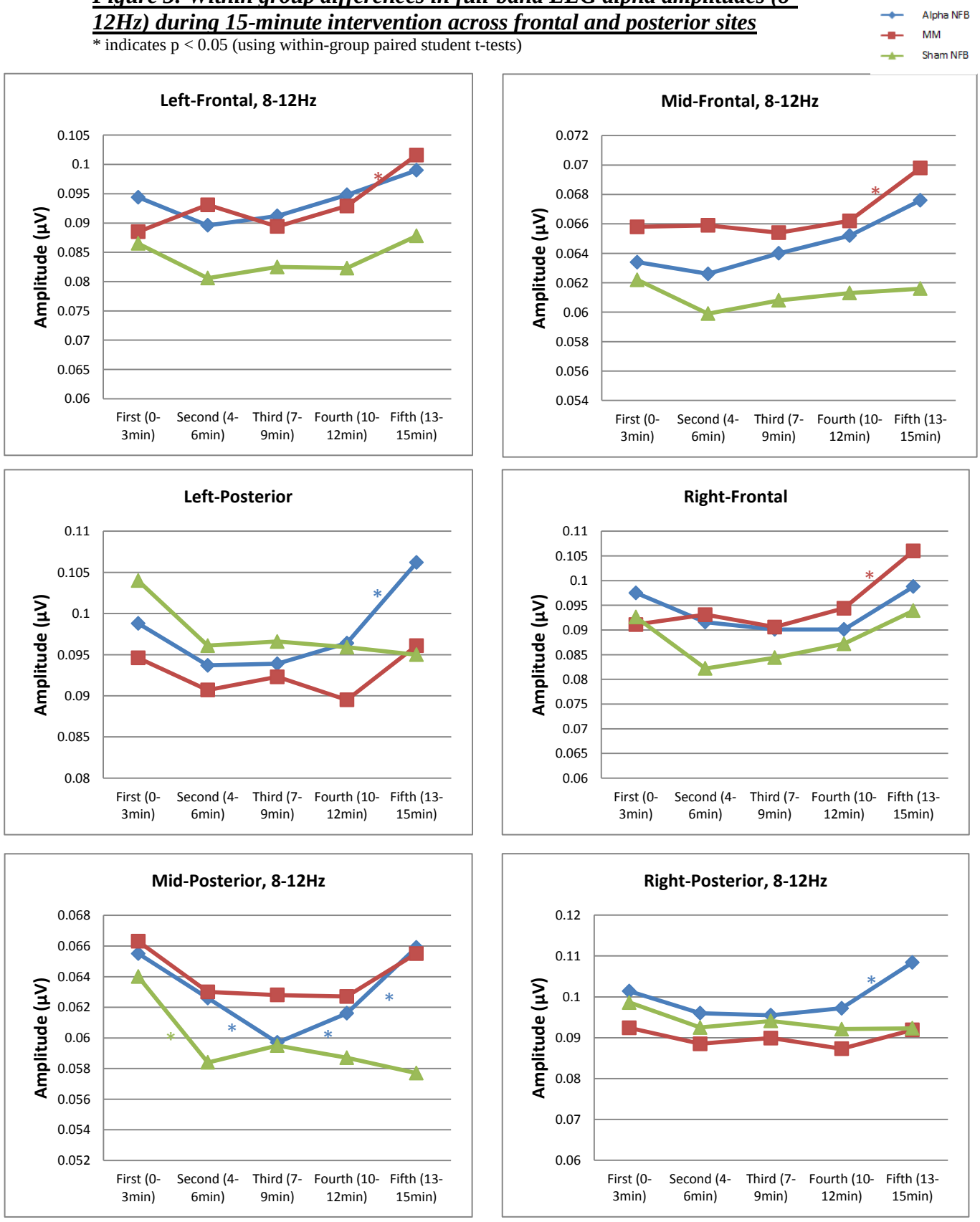


Table 6: Group differences in full-band EEG alpha amplitudes (8-12Hz) during 15-minute intervention

Intervention	Left-Frontal		Mid-Frontal		Right-Frontal		Left-Central		Mid-Central		Right-Central		Left-Posterior		Mid-Posterior		Right-Posterior	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
First (0-3min)																		
Alpha NFB	.0944	.0317	.0634	.0163	.0975	.0310	.0913	.0404	.0647	.0187	.0919	.0389	.0988	.0340	.0655	.0154	.1014	.0428
MM	.0885	.0376	.0658	.0206	.0911	.0329	.0786	.0300	.0694	.0247	.0788	.0218	.0946	.0334	.0663	.0247	.0924	.0284
Sham NFB	.0865	.0218	.0622	.0130	.0926	.0273	.0908	.0340	.0632	.0141	.0910	.0309	.1040	.0261	.0640	.0124	.0986	.0276
Second (4-6min)																		
Alpha NFB	.0896	.0283	.0626	.0146	.0916	.0290	.0796	.0289	.0650	.0163	.0856	.0331	.0937	.0328	.0626	.0141	.0960	.0390
MM	.0931	.0450	.0659	.0241	.0931	.0342	.0762	.0249	.0681	.0276	.0763	.0243	.0907	.0362	.0630	.0236	.0885	.0286
Sham NFB	.0806	.0215	.0599	.0139	.0822	.0234	.0798	.0318	.0588	.0152	.0835	.0434	.0961	.0239	.0584	.0128	.0925	.0278
Third (7-9min)																		
Alpha NFB	.0912	.0335	.0640	.0172	.0901	.0307	.0797	.0285	.0625	.0175	.0855	.0333	.0939	.0346	.0597	.0147	.0955	.0433
MM	.0894	.0395	.0654	.0238	.0906	.0326	.0746	.0270	.0681	.0267	.0799	.0318	.0923	.0367	.0628	.0244	.0899	.0317
Sham NFB	.0825	.0290	.0608	.0139	.0844	.0235	.0779	.0408	.0612	.0164	.0814	.0368	.0966	.0262	.0595	.0135	.0941	.0266
Fourth (10-12min)																		
Alpha NFB	.0948	.0391	.0652	.0167	.0901	.0245	.0802	.0309	.0649	.0201	.0843	.0339	.0964	.0328	.0616	.0150	.0972	.0388
MM	.0929	.0463	.0662	.0236	.0944	.0417	.0808	.0369	.0678	.0279	.0808	.0322	.0895	.0301	.0627	.0234	.0873	.0269
Sham NFB	.0823	.0161	.0613	.0120	.0872	.0193	.0749	.0300	.0617	.0162	.0799	.0287	.0959	.0228	.0587	.0120	.0921	.0259
Fifth (13-15min)																		
Alpha NFB	.0990	.0254	.0676	.0151	.0988	.0249	.0890	.0195	.0666	.0187	.1009	.0310	.1062	.0382	.0659	.0144	.1084	.0374
MM	.1016	.0478	.0698	.0241	.1060	.0442	.0914	.0398	.0711	.0266	.0888	.0341	.0961	.0348	.0655	.0226	.0919	.0308
Sham NFB	.0878	.0217	.0616	.0112	.0939	.0243	.0808	.0316	.0591	.0140	.0797	.0256	.0950	.0251	.0577	.0124	.0923	.0280

Main Effects and Interactions	Statistics
Group	$F(2, 61) = 0.260$, $\eta^2 = 0.008$, $p = 0.772$
Time	$F(4, 244) = 4.198$, $\eta^2 = 0.064$, $p = 0.010$*
Time × Group	$F(8, 244) = 0.987$, $\eta^2 = 0.031$, $p = 0.429$
Hemisphere	$F(2, 122) = 118.5$, $\eta^2 = 0.660$, $p < 0.001$**
Hemisphere × Group	$F(4, 122) = 0.844$, $\eta^2 = 0.027$, $p = 0.468$
Lobe	$F(2, 122) = 6.784$, $\eta^2 = 0.100$, $p = 0.004$*
Lobe × Group	$F(4, 122) = 0.888$, $\eta^2 = 0.028$, $p = 0.453$
Time × Hemisphere	$F(8, 488) = 2.513$, $\eta^2 = 0.040$, $p = 0.040$*
Time × Hemisphere × Group	$F(16, 488) = 0.740$, $\eta^2 = 0.024$, $p = 0.662$
Time × Lobe	$F(8, 488) = 1.779$, $\eta^2 = 0.028$, $p = 0.117$
Time × Lobe × Group	$F(16, 488) = 1.398$, $\eta^2 = 0.044$, $p = 0.181$
Hemisphere × Lobe	$F(4, 244) = 7.049$, $\eta^2 = 0.104$, $p < 0.001$**
Hemisphere × Lobe × Group	$F(8, 244) = 0.746$, $\eta^2 = 0.024$, $p = 0.614$
Time × Hemisphere × Lobe	$F(16, 976) = 1.031$, $\eta^2 = 0.017$, $p = 0.413$
Time × Hemisphere × Lobe × Group	$F(32, 976) = 1.045$, $\eta^2 = 0.033$, $p = 0.407$

Lower Alpha Band (8-10 Hz)

Referring to the lower alpha band (Table 7), post-hoc between-group comparisons were examined separately across the nine electrode sites at each of the five different intervention epochs, but no between-group differences were found. Instead only within-group differences across intervention periods were observed, as varying by electrode site and group (Figure 4).

Specifically, a within-group one-way ANOVA revealed that 8-10Hz EEG-alpha amplitudes varied significantly across the 5 intervention periods in the MM group in the left frontal, $F(4, 96) = 8.64$, $p = 0.001$, $\eta^2 = 0.265$, right frontal, $F(4, 96) = 9.11$, $p < 0.001$, $\eta^2 = 0.275$, left posterior, $F(4, 96) = 10.91$, $p < 0.001$, $\eta^2 = 0.312$, mid posterior, $F(4, 96) = 7.71$, $p = 0.001$, $\eta^2 = 0.243$, and right posterior regions, $F(4, 96) = 10.10$, $p < 0.001$, $\eta^2 = 0.296$. Repeated measures t-tests showed that MM participants significantly *reduced* their alpha amplitudes across left, right, and midline frontal and posterior sites after the first 3-minutes and again after the 7-9 minute periods; in contrast, differences at central sites were not observed.

Interestingly, significant changes were also seen in the Sham-NFB group with a significant one-way ANOVA revealing varying 8-10Hz EEG-alpha amplitudes across the 5 intervention periods in the left frontal, $F(4, 80) = 4.62$, $p = 0.013$, $\eta^2 = 0.188$, mid-frontal, $F(4, 80) = 3.28$, $p = 0.043$, $\eta^2 = 0.141$, right-frontal, $F(4, 80) = 6.04$, $p = 0.004$, $\eta^2 = 0.232$, left-posterior, $F(4, 80) = 6.83$, $p = 0.002$, $\eta^2 = 0.255$, mid-posterior, $F(4, 80) = 3.65$, $p = 0.036$, $\eta^2 = 0.154$, and right-posterior sites, $F(4, 80) = 4.62$, $p = 0.013$, $\eta^2 = 0.188$. However, in contrast with the MM group, the Sham-NFB group showed significant decreases in amplitude after the first 3-minutes and after the second 4-6 minute periods, but no further changes in amplitude thereafter. This pattern was consistent across all frontal and posterior lobe regions and again absent as an effect within central regions.

Finally, in striking contrast, the Alpha-NFB group did not show changes in their 8-10Hz rhythm across any of the nine electrode sites during any of the 5 intervention epochs.

Figure 4: Within group differences in lower-band EEG alpha amplitudes (8-10Hz) during 15-minute intervention across frontal and posterior sites

* indicates $p < 0.05$ (using within-group paired student t-tests)

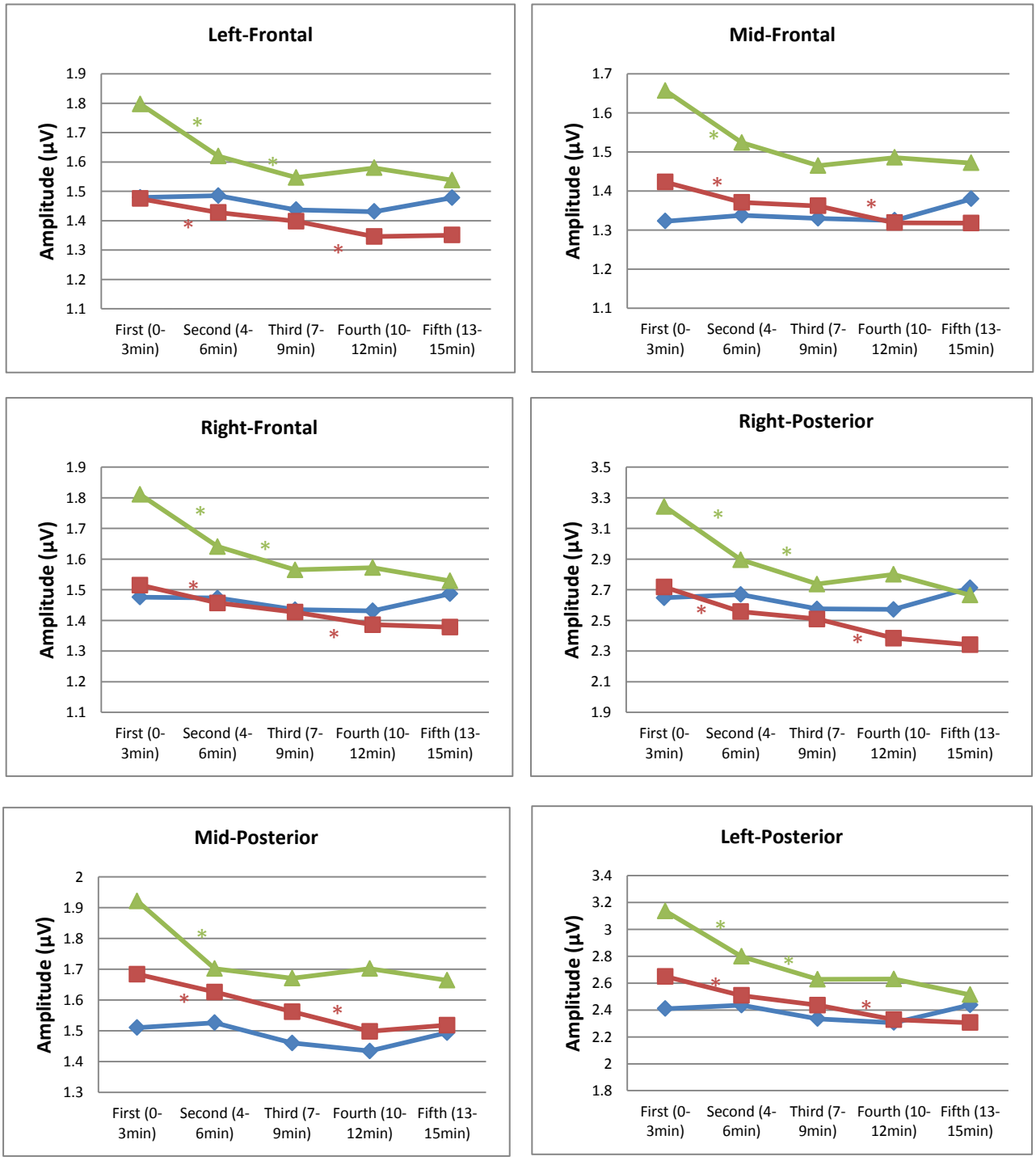


Table 7: Group differences in lower-band EEG alpha amplitudes (8-10Hz) during 15-minute intervention

Intervention	Left-Frontal		Mid-Frontal		Right-Frontal		Left-Central		Mid-Central		Right-Central		Left-Posterior		Mid-Posterior		Right-Posterior	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
First (0-3min)																		
Alpha NFB	1.479	0.645	1.323	0.612	1.476	0.639	1.261	0.567	1.198	0.523	1.355	0.596	2.410	1.337	1.510	0.761	2.648	1.297
MM	1.475	0.543	1.423	0.516	1.515	0.592	1.344	0.473	1.356	0.464	1.427	0.524	2.649	1.164	1.684	0.798	2.718	1.263
Sham NFB	1.797	0.676	1.657	0.593	1.811	0.734	1.559	0.750	1.543	0.582	1.575	0.752	3.136	1.320	1.922	0.912	3.244	1.305
Second (4-6min)																		
Alpha NFB	1.485	0.633	1.338	0.570	1.473	0.624	1.261	0.532	1.225	0.461	1.377	0.573	2.436	1.246	1.526	0.699	2.669	1.302
MM	1.428	0.537	1.371	0.523	1.457	0.583	1.319	0.475	1.303	0.460	1.381	0.512	2.508	1.180	1.626	0.778	2.557	1.238
Sham NFB	1.620	0.641	1.524	0.565	1.641	0.679	1.452	0.710	1.412	0.517	1.473	0.689	2.799	1.220	1.702	0.804	2.896	1.266
Third (7-9min)																		
Alpha NFB	1.437	0.616	1.330	0.583	1.435	0.599	1.234	0.477	1.233	0.483	1.341	0.531	2.335	1.259	1.460	0.655	2.575	1.331
MM	1.398	0.558	1.362	0.544	1.427	0.591	1.312	0.506	1.292	0.477	1.388	0.541	2.436	1.206	1.562	0.752	2.509	1.280
Sham NFB	1.547	0.667	1.465	0.578	1.565	0.717	1.398	0.695	1.373	0.540	1.430	0.701	2.628	1.307	1.671	0.833	2.737	1.344
Fourth (10-12min)																		
Alpha NFB	1.431	0.596	1.325	0.558	1.431	0.582	1.223	0.486	1.193	0.449	1.335	0.563	2.306	1.204	1.434	0.646	2.572	1.262
MM	1.346	0.525	1.319	0.524	1.386	0.561	1.273	0.487	1.232	0.433	1.330	0.509	2.328	1.156	1.498	0.681	2.384	1.176
Sham NFB	1.580	0.708	1.486	0.627	1.572	0.709	1.413	0.703	1.399	0.641	1.455	0.766	2.630	1.296	1.702	0.887	2.800	1.421
Fifth (13-15min)																		
Alpha NFB	1.478	0.652	1.380	0.621	1.487	0.619	1.252	0.512	1.249	0.520	1.357	0.565	2.438	1.319	1.494	0.705	2.713	1.387
MM	1.351	0.549	1.318	0.529	1.378	0.588	1.276	0.520	1.262	0.466	1.329	0.559	2.306	1.196	1.518	0.762	2.341	1.231
Sham NFB	1.538	0.700	1.472	0.625	1.529	0.684	1.387	0.689	1.419	0.677	1.428	0.730	2.514	1.210	1.664	0.915	2.665	1.347

Main Effects and Interactions	Statistics
Group	$F(2, 61) = 0.561$, $\eta^2 = 0.018$, $p = 0.573$
Time	$F(4, 244) = 7.112$, $\eta^2 = 0.104$, $p = 0.001$*
Time × Group	$F(8, 244) = 2.040$, $\eta^2 = 0.063$, $p = 0.084$
Hemisphere	$F(2, 122) = 109.56$, $\eta^2 = 0.642$, $p < 0.001$**
Hemisphere × Group	$F(4, 122) = 0.683$, $\eta^2 = 0.022$, $p = 0.557$
Lobe	$F(2, 122) = 162.98$, $\eta^2 = 0.728$, $p < 0.001$**
Lobe × Group	$F(4, 122) = 0.400$, $\eta^2 = 0.013$, $p = 0.700$
Time × Hemisphere	$F(8, 488) = 8.100$, $\eta^2 = 0.117$, $p < 0.001$**
Time × Hemisphere × Group	$F(16, 488) = 2.272$, $\eta^2 = 0.069$, $p = 0.033$*
Time × Lobe	$F(8, 488) = 10.11$, $\eta^2 = 0.142$, $p < 0.001$**
Time × Lobe × Group	$F(16, 488) = 2.300$, $\eta^2 = 0.070$, $p = 0.046$*
Hemisphere × Lobe	$F(4, 244) = 99.82$, $\eta^2 = 0.621$, $p < 0.001$**
Hemisphere × Lobe × Group	$F(8, 244) = 0.627$, $\eta^2 = 0.020$, $p = 0.623$
Time × Hemisphere × Lobe	$F(16, 976) = 2.863$, $\eta^2 = 0.045$, $p = 0.019$*
Time × Hemisphere × Lobe × Group	$F(32, 976) = 2.127$, $\eta^2 = 0.065$, $p = 0.028$*

Upper Alpha Band (10-12 Hz)

Referring to the upper alpha band (Table 8), given that the 4-way interaction of *Group, Time, Lobe* and *Hemisphere* was marginally significant ($p = 0.067$), and the percentage variance explained by the 4-way interaction was only trivially less between the 8-10Hz band ($\eta^2 = 0.065$) and the 10-12Hz band ($\eta^2 = 0.050$), post-hoc between-group comparisons were also examined for the upper alpha band. However, no between-group differences were found at any of the five different intervention epochs, across the nine electrode sites.

Within-group differences across intervention period were again observed, however, as varying by electrode site and group (Figure 5). Within-group one-way ANOVA analyses revealed that 10-12Hz EEG-alpha amplitudes varied significantly across the five intervention periods in the MM group in the left-posterior, $F(4, 96) = 5.16$, $p = 0.004$, $\eta^2 = 0.177$, mid-posterior, $F(4, 96) = 4.61$, $p = 0.01$, $\eta^2 = 0.161$, and right-posterior regions, $F(4, 96) = 7.68$, $p = 0.001$, $\eta^2 = 0.242$. Repeated measures t-tests showed that MM participants significantly *reduced* their upper alpha amplitudes across left, right, and midline posterior sites relative to the first 3-minute period.

Again, like the lower alpha band, similar changes were seen in the Sham-NFB group with a significant one-way ANOVA revealing varying 10-12Hz EEG-alpha amplitudes across the five intervention periods in the left-posterior, $F(4, 80) = 7.14$, $p = 0.001$, $\eta^2 = 0.263$, mid-posterior, $F(4, 80) = 6.57$, $p = 0.002$, $\eta^2 = 0.247$, and right-posterior regions, $F(4, 80) = 6.80$, $p = 0.001$, $\eta^2 = 0.254$. Similar to the MM group, Sham-NFB group also showed significant decreases in left, right, and midline amplitude after the first 3-minutes of intervention, with no significant changes thereafter.

Finally, as was found with the lower alpha band, a within group one-way ANOVA across the five intervention periods for the Alpha-NFB group did not show any significant changes in their 10-12Hz rhythm across any of the nine electrode sites.

Figure 5: Within group differences in upper-band EEG alpha amplitudes (10-12Hz) during 15-minute intervention across posterior sites

* indicates $p < 0.05$ (using within-group paired student t-tests)

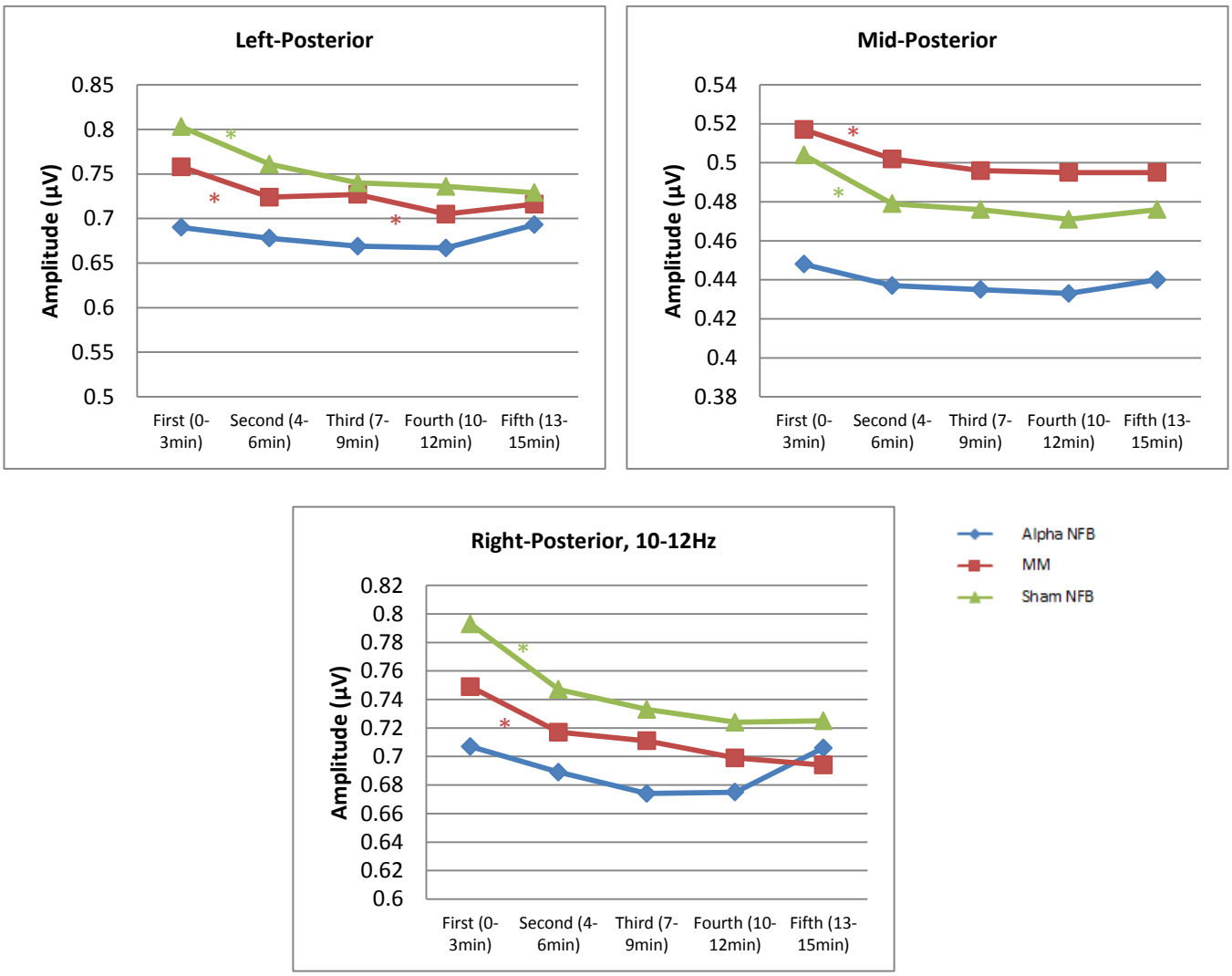


Table 8: Group differences in upper-band EEG alpha amplitudes (10-12Hz) during 15-minute intervention

Intervention	Left-Frontal		Mid-Frontal		Right-Frontal		Left-Central		Mid-Central		Right-Central		Left-Posterior		Mid-Posterior		Right-Posterior	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
First (0-3min)																		
Alpha NFB	0.520	0.088	0.443	0.112	0.539	0.094	0.522	0.137	0.422	0.109	0.533	0.121	0.690	0.164	0.448	0.116	0.707	0.193
MM	0.580	0.187	0.516	0.177	0.607	0.194	0.545	0.125	0.500	0.185	0.559	0.131	0.758	0.220	0.517	0.165	0.749	0.205
Sham NFB	0.560	0.122	0.508	0.133	0.594	0.139	0.602	0.180	0.477	0.136	0.602	0.158	0.803	0.189	0.504	0.125	0.793	0.189
Second (4-6min)																		
Alpha NFB	0.525	0.079	0.450	0.109	0.533	0.085	0.502	0.095	0.425	0.105	0.518	0.106	0.678	0.146	0.437	0.095	0.689	0.174
MM	0.589	0.203	0.512	0.171	0.593	0.166	0.532	0.113	0.494	0.173	0.547	0.134	0.724	0.219	0.502	0.155	0.717	0.200
Sham NFB	0.560	0.129	0.508	0.132	0.569	0.126	0.566	0.168	0.469	0.143	0.576	0.183	0.761	0.174	0.479	0.117	0.747	0.175
Third (7-9min)																		
Alpha NFB	0.535	0.090	0.466	0.129	0.546	0.098	0.495	0.089	0.432	0.124	0.513	0.109	0.669	0.145	0.435	0.098	0.674	0.175
MM	0.582	0.186	0.516	0.182	0.591	0.160	0.533	0.127	0.487	0.174	0.558	0.143	0.727	0.228	0.496	0.153	0.711	0.202
Sham NFB	0.565	0.138	0.510	0.136	0.572	0.125	0.544	0.172	0.474	0.141	0.558	0.159	0.740	0.182	0.476	0.114	0.733	0.164
Fourth (10-12min)																		
Alpha NFB	0.556	0.126	0.471	0.141	0.550	0.105	0.507	0.119	0.434	0.127	0.530	0.129	0.667	0.128	0.433	0.097	0.675	0.153
MM	0.598	0.212	0.519	0.193	0.599	0.175	0.548	0.150	0.490	0.193	0.554	0.147	0.705	0.214	0.495	0.162	0.699	0.193
Sham NFB	0.564	0.110	0.509	0.121	0.588	0.110	0.537	0.155	0.472	0.133	0.549	0.124	0.736	0.167	0.471	0.107	0.724	0.161
Fifth (13-15min)																		
Alpha NFB	0.541	0.101	0.463	0.127	0.541	0.088	0.511	0.083	0.434	0.124	0.561	0.128	0.693	0.160	0.440	0.101	0.706	0.172
MM	0.611	0.211	0.521	0.185	0.621	0.186	0.564	0.146	0.495	0.181	0.559	0.140	0.716	0.217	0.495	0.152	0.694	0.190
Sham NFB	0.582	0.116	0.519	0.117	0.618	0.124	0.551	0.145	0.483	0.133	0.552	0.122	0.729	0.161	0.476	0.110	0.725	0.158

Main Effects and Interactions	Statistics
Group	$F(2, 61) = 0.926$, $\eta^2 = 0.029$, $p = 0.402$
Time	$F(4, 244) = 3.160$, $\eta^2 = 0.049$, $p = 0.033$*
Time × Group	$F(8, 244) = 0.855$, $\eta^2 = 0.027$, $p = 0.516$
Hemisphere	$F(2, 122) = 164.37$, $\eta^2 = 0.729$, $p < 0.001$**
Hemisphere × Group	$F(4, 122) = 0.577$, $\eta^2 = 0.019$, $p = 0.633$
Lobe	$F(2, 122) = 63.55$, $\eta^2 = 0.510$, $p < 0.001$**
Lobe × Group	$F(4, 122) = 0.343$, $\eta^2 = 0.011$, $p = 0.780$
Time × Hemisphere	$F(8, 488) = 2.075$, $\eta^2 = 0.033$, $p = 0.084$
Time × Hemisphere × Group	$F(16, 488) = 0.926$, $\eta^2 = 0.029$, $p = 0.496$
Time × Lobe	$F(8, 488) = 8.342$, $\eta^2 = 0.120$, $p < 0.001$**
Time × Lobe × Group	$F(16, 488) = 1.456$, $\eta^2 = 0.046$, $p = 0.166$
Hemisphere × Lobe	$F(4, 244) = 60.71$, $\eta^2 = 0.499$, $p < 0.001$**
Hemisphere × Lobe × Group	$F(8, 244) = 0.819$, $\eta^2 = 0.026$, $p = 0.536$
Time × Hemisphere × Lobe	$F(16, 976) = 1.505$, $\eta^2 = 0.024$, $p = 0.156$
Time × Hemisphere × Lobe × Group	$F(32, 976) = 1.605$, $\eta^2 = 0.050$, $p = 0.067$

3.4 Effects of Intervention on Stroop Task

Two participants from the EEG-Alpha NFB and Sham-NFB groups did not complete the Stroop task and were therefore excluded from analyses (Subject: 2195, 6408). One participant was additionally excluded based on abnormally low accuracy, with z-scores of -7.4 and -5.6 for congruent and incongruent conditions, respectively. Results for behavioural performance, event-related alpha desynchronization in the lower and upper alpha bands, and event-related potentials were analyzed separately and reported in Tables 9, 10, 11 and 12, respectively.

Stroop Behavioural Performance

Table 9 reports the results for behavioural performance of the Stroop task. As expected, main effects for *Congruency* were found for both reaction time, $F(1,63) = 62.2$, $p < 0.001$, $\eta^2 = 0.497$, and accuracy, $F(1, 66) = 33.5$, $p < 0.001$, $\eta^2 = 0.337$, with incongruent trials associated with increased errors and slower reaction time. However, the main effect of *Group* and the interaction between *Group* and *Condition* were non-significant.

Table 9: Group Differences in Behavioural Stroop Performance (reaction time and accuracy)

	EEG-Alpha NFB	MM	Sham-NFB	Statistics		
				Group F(2, 63) (η^2)	Congruency F(1, 63) (η^2)	Interaction F(2,63) (η^2)
Reaction Time (ms)				0.915 (0.028), p=0.41	62.2 (0.497), p<0.001**	0.124 (0.004), p=0.88
Congruent	329.7 (97.2)	329.9 (85.1)	295.1 (66.1)			
Incongruent	417.2 (125.3)	414.3 (89.0)	387.4 (83.3)			
Accuracy				1.25 (0.038), p=0.29	33.5 (0.337), p <0.001**	1.42 (0.043), p=0.25
Congruent	0.95 (0.05)	0.96 (0.03)	0.94 (0.05)			
Incongruent	0.92 (0.09)	0.93 (0.05)	0.89 (0.09)			

Stroop behavioural data, reported as Means (SD)

Stroop Event-Related Alpha Desynchronization and Synchronization (ERD/S)

Participants were only included in final analyses if they retained >40% of their ERD/S data. As such, 3 participants were removed from the EEG-Alpha NFB group (Subjects: 4107 and 6521, <10%; Subject: 4507, 30.6%), 3 from the MM group (Subjects: 2024 and 8608, <10%; Subject: 7756, 33.3%), and 3 from the Sham-NFB group (Subject: 2770, <10%; Subject: 2814 and 5217, 22.9% and 19.4%, respectively).

Tables 10 and 11 report the results for EEG-Alpha ERD and ERS following stimulus presentation during the Stroop task (Tables 10 and 11 report results from split-plot ANOVA of the lower and upper alpha bands, respectively). Various main effects and interactions were observed for the factors *Congruency, Lobe,* and *Hemisphere* for both alpha bands. No main effects of *Group* were found across either of the alpha bands for ERD/S values in either of the 200-400ms or 400-600ms post-stimulus time windows. However, differential interaction effects involving *Congruency, Lobe,* and *Hemisphere* were observed by group depending on the specific alpha band and time window of assessment.

Lower Alpha Band (8-10 Hz) during 200-400ms and 400-600ms time periods

The lower alpha band (Table 10) revealed only significant main effects for Lobe and Hemisphere during the first 200-400ms post-stimulus interval. However, during the following 400-600ms post-stimulus interval, a significant *Congruency* × *Hemisphere* × *Group* interaction was found, $F(4,108) = 2.808$, $\eta 2 = 0.094$, $p = 0.029$. Subsequent analyses during this time period did not reveal any further differences between groups in their ERD levels across hemispheres nor congruency. Pairwise t-tests analyzing hemispheric ERD patterns across the 400-600ms interval (Figure 6) revealed significantly weaker ERD in the midline region for the Alpha-NFB group in congruent conditions, relative to the right, $t(15) = 3.6$, $p = 0.003$, and left hemispheres, $t(15) = -3.8$, $p = 0.001$. This pattern of desynchronization was also present for MM and Sham-NFB groups, but only in the incongruent condition.

Figure 6: Hemispheric patterns of lower-band EEG alpha (8-10Hz) ERD during 400-600ms post-stimulus interval

* indicates $p < 0.05$ (using within-group paired student t-tests)

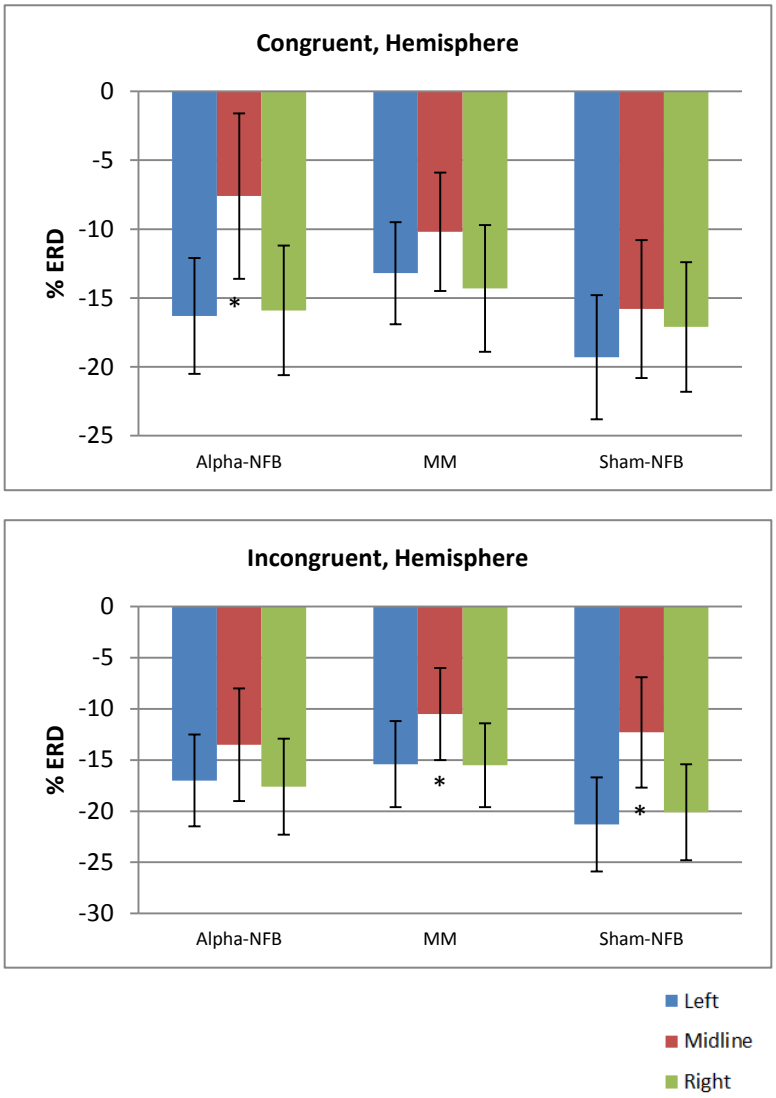


Table 10: Group differences in lower-band EEG alpha ERD (8-10Hz) during Stroop task

Time post-stimulus	Left-Frontal		Mid-Frontal		Right-Frontal		Left-Central		Mid-Central		Right-Central		Left-Posterior		Mid-Posterior		Right-Posterior	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
200-400ms																		
Congruent																		
Alpha NFB	-5.74	17.93	-0.69	24.67	-6.88	17.11	-7.98	19.93	-0.11	23.19	-8.30	15.81	-19.21	18.84	-12.00	19.66	-23.71	15.01
MM	-3.92	19.71	-0.37	25.48	-1.86	27.67	-10.93	18.44	-2.07	30.22	-11.19	15.93	-17.99	19.15	-15.12	23.69	-22.58	17.84
Sham NFB	-11.21	20.46	-6.23	22.30	-9.44	23.51	-14.32	16.61	-3.93	23.52	-12.80	19.65	-25.04	20.00	-15.53	20.33	-25.97	20.34
Incongruent																		
Alpha NFB	-12.99	19.74	-7.91	22.17	-6.22	21.49	-15.53	16.08	-3.33	25.90	-6.81	22.89	-22.61	20.94	-14.80	23.37	-22.30	19.92
MM	-1.63	24.26	-1.48	22.56	-5.76	22.48	-10.57	13.20	-3.80	19.72	-10.79	15.76	-21.51	16.23	-14.48	17.35	-20.41	18.32
Sham NFB	-9.48	21.04	-0.17	26.98	-5.81	25.23	-10.72	19.53	-0.87	20.60	-11.00	17.74	-23.03	23.82	-18.02	20.57	-23.11	21.67
400-600ms																		
Congruent																		
Alpha NFB	-6.93	23.27	-5.29	26.66	-6.80	21.74	-16.06	18.00	-0.99	27.70	-13.39	23.57	-25.21	17.49	-16.23	30.36	-25.61	20.09
MM	-3.55	21.16	-7.20	18.47	-5.13	24.92	-12.66	16.84	-5.86	21.87	-14.35	21.90	-23.39	21.58	-17.54	27.74	-23.54	22.98
Sham NFB	-8.65	24.73	-7.98	25.12	-4.08	31.32	-19.14	20.62	-13.46	23.36	-18.99	18.84	-30.16	17.41	-26.01	20.57	-28.24	19.58
Incongruent																		
Alpha NFB	-11.90	19.90	-11.74	22.07	-9.40	18.96	-16.30	18.77	-8.29	23.88	-16.87	20.42	-22.79	19.38	-20.47	26.58	-26.63	22.09
MM	-6.78	24.35	-7.05	21.93	-7.97	21.31	-15.44	18.49	-8.98	21.80	-13.88	20.14	-25.09	22.22	-17.84	27.56	-24.94	23.89
Sham NFB	-9.41	28.63	-4.12	24.96	-7.91	26.50	-22.01	19.60	-1.86	29.43	-20.31	21.49	-30.44	20.31	-27.08	23.66	-28.94	21.82

Main Effects and Interactions	Statistics
Group	$F(2,54) = 0.134$, $\eta^2 = 0.005$, $p = 0.875$
Congruency	$F(1,54) = 0.092$, $\eta^2 = 0.002$, $p = 0.763$
Congruency × Group	$F(2,54) = 1.611$, $\eta^2 = 0.056$, $p = 0.209$
Hemisphere	$F(2,108) = 24.70$, $\eta^2 = 0.314$, $p < 0.001$**
Hemisphere × Group	$F(4,108) = 0.562$, $\eta^2 = 0.020$, $p = 0.626$
Lobe	$F(2,108) = 65.94$, $\eta^2 = 0.550$, $p < 0.001$**
Lobe × Group	$F(4,108) = 0.833$, $\eta^2 = 0.030$, $p = 0.507$
Congruency × Hemisphere	$F(2,108) = 1.453$, $\eta^2 = 0.026$, $p = 0.239$
Congruency × Hemisphere × Group	$F(4,108) = 1.141$, $\eta^2 = 0.041$, $p = 0.338$
Congruency × Lobe	$F(2,108) = 0.036$, $\eta^2 = 0.001$, $p = 0.965$
Congruency × Lobe × Group	$F(4,108) = 0.758$, $\eta^2 = 0.027$, $p = 0.555$
Hemisphere × Lobe	$F(4,216) = 2.168$, $\eta^2 = 0.039$, $p = 0.095$
Hemisphere × Lobe × Group	$F(8,216) = 0.263$, $\eta^2 = 0.010$, $p = 0.951$
Congruency × Hemisphere × Lobe	$F(4,216) = 0.240$, $\eta^2 = 0.004$, $p = 0.893$
Congruency × Hemisphere × Lobe × Group	$F(8,216) = 1.126$, $\eta^2 = 0.040$, $p = 0.349$

200-400ms

Main Effects and Interactions	Statistics
Group	$F(2,54) = 0.198$, $\eta^2 = 0.007$, $p = 0.821$
Congruency	$F(1,54) = 1.076$, $\eta^2 = 0.020$, $p = 0.304$
Congruency × Group	$F(2,54) = 0.566$, $\eta^2 = 0.021$, $p = 0.571$
Hemisphere	$F(2,108) = 18.97$, $\eta^2 = 0.260$, $p < 0.001$**
Hemisphere × Group	$F(4,108) = 0.565$, $\eta^2 = 0.020$, $p = 0.689$
Lobe	$F(2,108) = 86.69$, $\eta^2 = 0.616$, $p < 0.001$**
Lobe × Group	$F(4,108) = 1.497$, $\eta^2 = 0.053$, $p = 0.211$
Congruency × Hemisphere	$F(2,108) = 0.288$, $\eta^2 = 0.005$, $p = 0.751$
Congruency × Hemisphere × Group	$F(4,108) = 2.808$, $\eta^2 = 0.094$, $p = 0.029$*
Congruency × Lobe	$F(2,108) = 0.544$, $\eta^2 = 0.010$, $p = 0.582$
Congruency × Lobe × Group	$F(4,108) = 0.737$, $\eta^2 = 0.027$, $p = 0.569$
Hemisphere × Lobe	$F(4,216) = 5.919$, $\eta^2 = 0.099$, $p < 0.001$**
Hemisphere × Lobe × Group	$F(8,216) = 0.654$, $\eta^2 = 0.024$, $p = 0.731$
Congruency × Hemisphere × Lobe	$F(4,216) = 0.794$, $\eta^2 = 0.014$, $p = 0.531$
Congruency × Hemisphere × Lobe × Group	$F(8,216) = 1.661$, $\eta^2 = 0.058$, $p = 0.109$

400-600ms

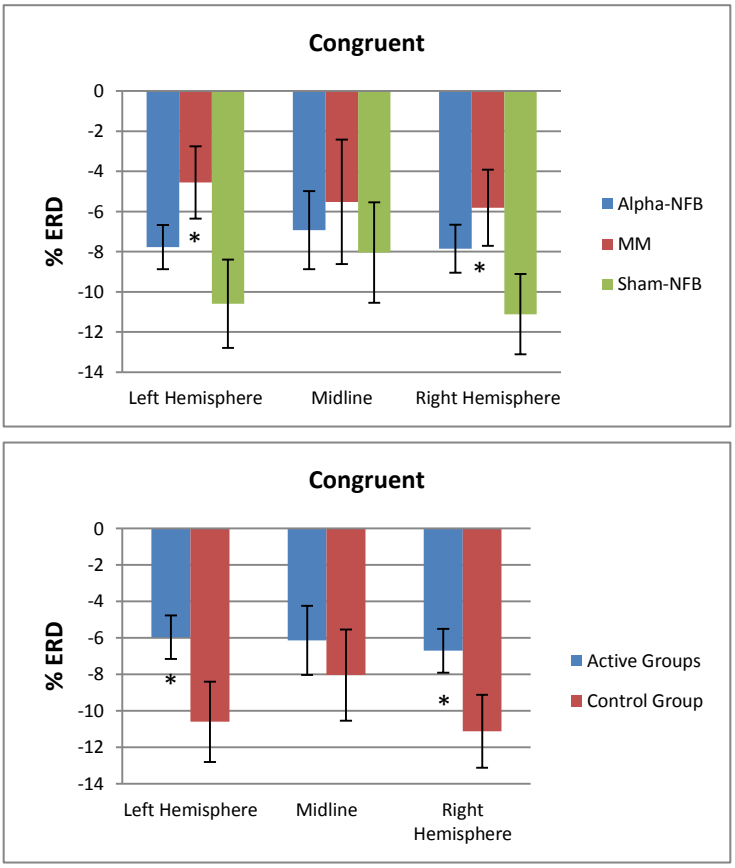
Upper Alpha Band (10-12 Hz) during 200-400ms time period

The upper alpha band revealed significant *Congruency* × *Hemisphere* × *Group* interaction for the first 200-400ms post-stimulus, $F(4,108) = 2.581$, $\eta 2 = 0.087$, $p = 0.05$ (Table 11). Post-hoc analyses revealed that in the congruent condition, MM participants had significantly weaker ERD in the left hemisphere, $t(39) = 2.2$, $p = 0.038$, and marginally significant in the right hemisphere, $t(39) = 1.89$, $p = 0.066$, relative to Sham-NFB (Figure 7). When considering the effects of both active groups combined in comparison with the Sham group, MM and Alpha-NFB were found to exhibit a significantly weaker ERD in the right hemisphere, $t(56) = 1.9$, $p = 0.05$, and left hemisphere, $t(56) = 2.1$, $p = 0.04$.

Pairwise t-tests analyzing within-group differences revealed no distinct ERD patterns across hemispheres. In other words, the extent of ERD across each hemisphere was largely equivalent for each group.

Figure 7: Group differences in upper-band EEG alpha ERD (10-12Hz) during 200-400ms post-stimulus interval of Stroop Task

* indicates $p < 0.05$ (using between-group student t-tests)

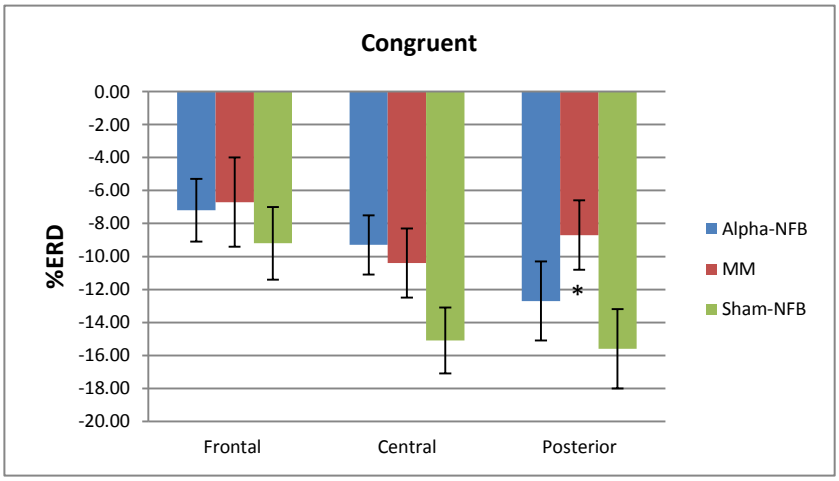


Upper Alpha Band (10-12 Hz) during 400-600ms time period

During the 400-600ms post-stimulus period (Table 11), a significant *Congruency* × *Lobe* × *Group* interaction was also found, $F(4,108) = 3.160$, $\eta 2 = 0.105$, $p = 0.025$. Post-hoc analyses revealed group differences in the *Congruent* condition, with MM participants exhibiting weaker ERD in the posterior lobe relative to the Sham-NFB group, $t(39) = 2.2$, $p = 0.03$ (Figure 8). Further, when considering the two active interventions combined, ERD was marginally weaker than the non-active control group at the posterior, $t(56) = 1.9$, $p = 0.06$, and central regions, $t(56) = 1.9$, $p = 0.067$. Within-group differences in distinct ERD patterns across lobes and hemispheres revealed an overall weaker frontal ERD relative to central and posterior lobes, a pattern seen across all groups and conditions (Figure 9). Furthermore, ERD was largely equivalent across hemispheres in all groups.

Figure 8: Group differences in upper-band EEG alpha ERD (10-12Hz) during 400-600ms post-stimulus interval of Stroop Task

* indicates $p < 0.05$ (using between-group student t-tests)



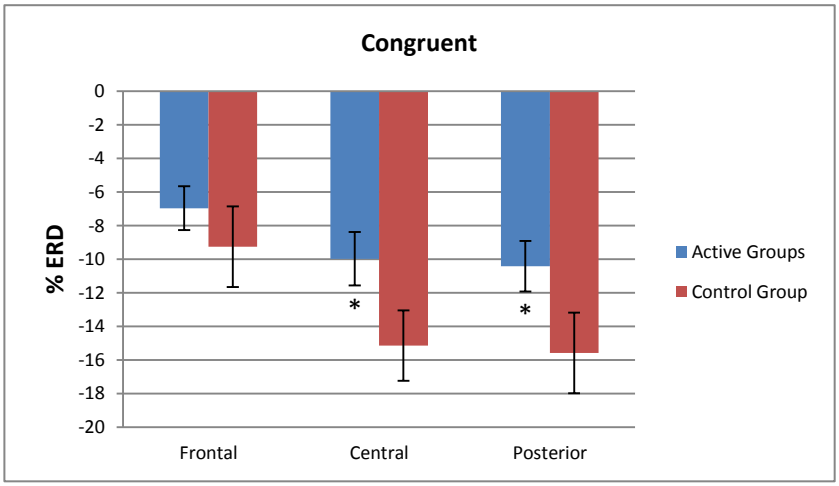
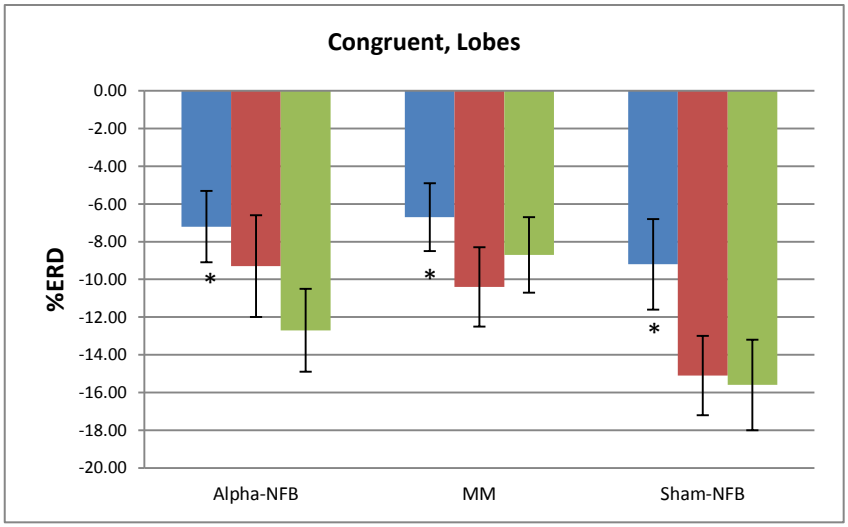


Figure 9: Lobe patterns of upper-band EEG alpha (10-12Hz) ERD during 400-600ms post-stimulus interval

* indicates $p < 0.05$ (using within-group paired student t-tests)



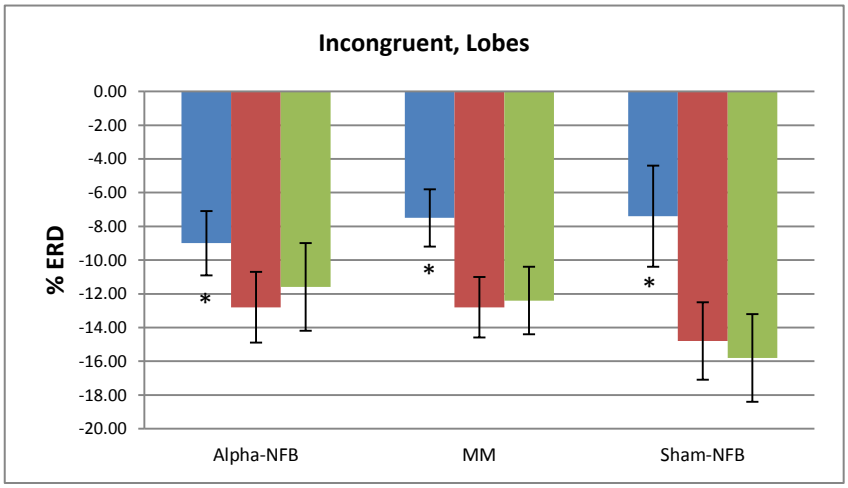


Table 11: Group differences in upper-band EEG alpha ERD (10-12Hz) during Stroop task

Time post-stimulus	Left-Frontal		Mid-Frontal		Right-Frontal		Left-Central		Mid-Central		Right-Central		Left-Posterior		Mid-Posterior		Right-Posterior	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
200-400ms																		
Congruent																		
Alpha NFB	-6.51	6.66	-6.82	11.16	-6.14	7.64	-8.90	5.97	-5.98	11.93	-9.32	6.94	-6.99	5.77	-6.72	7.13	-7.20	8.62
MM	-0.03	11.64	-5.51	14.60	-0.77	10.12	-9.50	8.67	-5.71	19.17	-10.02	7.73	-4.16	10.74	-5.35	12.97	-6.65	13.74
Sham NFB	-7.48	10.36	-9.98	13.12	-6.28	11.04	-11.65	9.25	-7.19	12.55	-12.88	10.52	-12.66	13.56	-6.95	11.80	-14.22	11.02
Incongruent																		
Alpha NFB	-8.24	10.77	-7.13	13.13	-5.50	10.10	-8.96	9.55	-5.57	14.07	-9.31	7.83	-9.93	10.26	-8.90	10.58	-6.56	13.65
MM	-0.18	11.99	-3.27	12.98	0.46	13.25	-8.88	8.84	-5.57	15.44	-8.29	7.54	-6.02	12.59	-3.69	14.36	-6.64	11.85
Sham NFB	-6.53	10.23	-11.28	13.53	-4.78	14.46	-11.65	10.98	-10.96	16.11	-12.22	10.76	-13.21	16.07	-11.51	11.49	-12.72	12.22
400-600ms																		
Congruent																		
Alpha NFB	-5.55	8.36	-9.36	10.61	-6.63	7.56	-9.78	10.55	-8.63	11.55	-9.47	15.67	-12.98	9.65	-11.98	14.10	-13.81	8.30
MM	-5.99	8.26	-9.42	12.22	-4.83	8.16	-11.78	9.30	-9.08	16.25	-10.59	8.58	-6.59	9.10	-11.80	10.03	-7.68	12.14
Sham NFB	-8.11	10.82	-14.26	12.21	-5.37	12.63	-15.17	11.20	-14.37	13.22	-15.88	9.02	-13.68	12.99	-16.73	9.55	-16.35	11.72
Incongruent																		
Alpha NFB	-8.90	7.50	-10.87	10.77	-7.36	6.01	-13.42	11.26	-11.17	12.10	-13.86	7.33	-10.92	10.55	-13.09	12.34	-10.85	12.22
MM	-6.45	8.74	-10.94	11.56	-4.47	9.18	-13.03	8.84	-10.39	10.95	-12.45	7.21	-11.25	9.18	-12.18	10.16	-10.95	10.90
Sham NFB	-6.02	13.10	-12.78	14.59	-4.50	15.83	-15.94	9.20	-13.85	14.93	-16.02	10.09	-16.31	14.43	-16.06	11.66	-15.04	13.06

Main Effects and Interactions	Statistics
Group	$F(2,54) = 1.720$, $\eta^2 = 0.060$, $p = 0.189$
Congruency	$F(1,54) = 0.064$, $\eta^2 = 0.001$, $p = 0.801$
Congruency × Group	$F(2,54) = 0.295$, $\eta^2 = 0.011$, $p = 0.746$
Hemisphere	$F(2,108) = 0.525$, $\eta^2 = 0.010$, $p = 0.555$
Hemisphere × Group	$F(4,108) = 0.211$, $\eta^2 = 0.008$, $p = 0.901$
Lobe	$F(2,108) = 10.51$, $\eta^2 = 0.163$, $p < 0.001$**
Lobe × Group	$F(4,108) = 1.952$, $\eta^2 = 0.067$, $p = 0.107$
Congruency × Hemisphere	$F(2,108) = 2.845$, $\eta^2 = 0.050$, $p = 0.062$
Congruency × Hemisphere × Group	$F(4,108) = 2.581$, $\eta^2 = 0.087$, $p = 0.053$*
Congruency × Lobe	$F(2,108) = 1.395$, $\eta^2 = 0.025$, $p = 0.252$
Congruency × Lobe × Group	$F(4,108) = 0.280$, $\eta^2 = 0.010$, $p = 0.890$
Hemisphere × Lobe	$F(4,216) = 7.541$, $\eta^2 = 0.123$, $p < 0.001$**
Hemisphere × Lobe × Group	$F(8,216) = 1.120$, $\eta^2 = 0.040$, $p = 0.351$
Congruency × Hemisphere × Lobe	$F(4,216) = 0.504$, $\eta^2 = 0.009$, $p = 0.732$
Congruency × Hemisphere × Lobe × Group	$F(8,216) = 0.402$, $\eta^2 = 0.015$, $p = 0.919$

200-400ms

Main Effects and Interactions	Statistics
Group	$F(2,54) = 1.065$, $\eta^2 = 0.038$, $p = 0.352$
Congruency	$F(1,54) = 0.944$, $\eta^2 = 0.017$, $p = 0.335$
Congruency × Group	$F(2,54) = 0.516$, $\eta^2 = 0.019$, $p = 0.600$
Hemisphere	$F(2,108) = 3.886$, $\eta^2 = 0.067$, $p = 0.029$*
Hemisphere × Group	$F(4,108) = 0.442$, $\eta^2 = 0.016$, $p = 0.754$
Lobe	$F(2,108) = 22.73$, $\eta^2 = 0.296$, $p < 0.001$**
Lobe × Group	$F(4,108) = 1.684$, $\eta^2 = 0.059$, $p = 0.159$
Congruency × Hemisphere	$F(2,108) = 0.590$, $\eta^2 = 0.011$, $p = 0.522$
Congruency × Hemisphere × Group	$F(4,108) = 0.179$, $\eta^2 = 0.007$, $p = 0.922$
Congruency × Lobe	$F(2,108) = 1.729$, $\eta^2 = 0.031$, $p = 0.189$
Congruency × Lobe × Group	$F(4,108) = 3.160$, $\eta^2 = 0.105$, $p = 0.025$*
Hemisphere × Lobe	$F(4,216) = 7.824$, $\eta^2 = 0.127$, $p < 0.001$*
Hemisphere × Lobe × Group	$F(8,216) = 0.538$, $\eta^2 = 0.020$, $p = 0.799$
Congruency × Hemisphere × Lobe	$F(4,216) = 0.652$, $\eta^2 = 0.012$, $p = 0.598$
Congruency × Hemisphere × Lobe × Group	$F(8,216) = 1.390$, $\eta^2 = 0.049$, $p = 0.215$

400-600ms

Stroop Event-Related Potentials (P300)

Participants were only included in final analyses of ERPs if they retained >40% of their ERP data. As such, 3 participants were removed from the EEG-Alpha NFB group (Subjects: 4107 and 6521, <10%; Subject: 4507, 30.6%), 3 from MM group (Subjects: 2024 and 8608, <10%; Subject: 7756, 33.3%), and 3 from Sham-NFB group (Subject: 2770, <10%; Subject: 2814 and 5217, 22.9% and 19.4%, respectively). The analysis of the P300 component focused on the amplitude maximum at electrode Pz (central posterior). Table 12 depicts amplitude and latency measures of the P300 component.

P300 Amplitude

Referring to amplitude, there was no significant main effect of *Group* nor *Congruency*, as well as no significant interaction. Planned comparisons revealed only a non-significant trend towards lower peak P300 amplitude for incongruent relative to congruent stimuli in the Alpha-NFB group, $t(14) = 1.9$, $p = 0.08$. This difference that was not present within the MM and Sham-NFB groups.

P300 Latency

Referring to latency, there was only a non-significant trend ($p = .076$) toward longer latencies for congruent vs. incongruent trials; no main or interaction effects involving *Group* were observed.

Table 12: P300 Amplitude and Latency during Stroop Task

	EEG-Alpha NFB	MM	Sham-NFB	Statistics		
				Group F(2, 63) (η^2)	Congruency F(1, 53) (η^2)	Interaction F(2,53) (η^2)
P300 Amplitude (μV)				0.76 (0.028), p = 0.471	0.49 (0.009), p = 0.485	0.54 (0.02), p = 0.589
Congruent	7.44 (8.8)	7.51 (10.0)	5.65 (10.4)			
Incongruent	3.41 (9.4)	8.12 (11.3)	5.18 (8.2)			
P300 Latency (ms)				0.26 (0.01), p = 0.772	3.28 (0.058), p = 0.076	1.34 (0.048), p = 0.269
Congruent	476.6 (124.2)	456.7 (106.2)	486.43 (114.2)			
Incongruent	449.3 (126.8)	452.0 (104.9)	401.9 (85.8)			

Chapter 4 – Discussion

The primary objective of this study was to contribute to the growing literature associating the EEG-Alpha rhythm and attentional control by comparing two interventions that are both known to enhance the alpha rhythm. Whereas MM directly trains attentional control, with subsequent indirect enhancements of the alpha rhythm, Alpha-NFB directly enhances the alpha rhythm through a brain-computer interface. Accordingly, this study directly compared these two active interventions on their ability to enhance the 8-12Hz EEG-Alpha rhythm, and subsequently their differential effects on attentional control performance, relative to a non-active Sham-NFB control group. We hypothesized that the two active interventions would enhance the EEG-Alpha rhythm greater than the Sham-NFB group, and that these changes would be further reflected in neural processes (ERPs and ERDs) and improved performance on an attentional task (Stroop). Further, we sought to identify potential specific effects of the two active interventions by comparing the response to MM and NFB.

4.1 Modulation of the Full EEG-Alpha Rhythm (8-12Hz)

No differences were found between groups either during the intervention or at the post-intervention time period for the full alpha frequency band (8-12Hz). The lack of between group differences may allude to the need for multiple sessions of active intervention training in order to induce lasting and detectable changes in the EEG-Alpha rhythm. This is reflected in the fact that differential modulation of the EEG-Alpha amplitude was seen *within* groups during each of the respective interventions. Planned comparisons within each group for their differential ability to modulate the alpha rhythm during the intervention period revealed that the active intervention groups MM and Alpha-NFB exhibited significant *increases* in the full band alpha amplitude, whereas the Sham-NFB significantly *decreased* their alpha amplitude. These findings suggest the promise of additional data collection; the lack of a significant between-group difference may be a type-2 error.

Almost all studies of MM and NFB on their ability to modulate the alpha rhythm relative to controls have used multiple session designs. Referring to MM, to the best of our knowledge, no studies have attempted to investigate the effect of a brief 15-minute MM session on EEG-Alpha amplitude before, during, and after the intervention. Indeed, MM practice is usually linked with increases in EEG-Alpha amplitude in studies sampling participants that have received multiple sessions of meditation practice or are long-term experienced meditators from a wide array of contemplative practices and techniques (Cahn and Polich, 2006). In comparison, our study focused only on the specific factor of attention training in MM practice, which was associated with increases in EEG-Alpha amplitude in the frontal lobe during the MM intervention. This alludes to a potential functional significance of alpha-band activity for attentional processes, as alpha amplitude did change in the expected positive direction during MM attentional training. This finding accords with the literature describing increases in EEG-Alpha during processes involving internalized attention such as MM. However, longer term MM practice conducted over multiple sessions may be needed to significantly enhance and stabilize long-term changes in the full EEG alpha band.

Referring to NFB training of the alpha rhythm, within-group analyses also revealed significant increases in full band (8-12 Hz) EEG-Alpha amplitudes in Alpha-NFB participants across the 15-minute intervention period. Although this change seems reflective of the Alpha-NFB enhancement training, especially since the amplitude increases were primarily observed at the posterior regions where NFB training had occurred (i.e. parietal Pz site), the brief session was not sufficient to produce long-lasting increases that distinguished the effects of NFB from the MM or Sham-NFB groups. Indeed, most studies have suggested that multiple sessions are needed for the participant to establish associative relations between modifications in their EEG-Alpha amplitude and changes to internal states (Vernon et al., 2009; Konareva, 2005). This is consistently reported in studies describing changes in EEG-Alpha only after multiple NFB sessions taking place over a period of weeks (Angelakis et al., 2007; Boxtel et al., 2012; Dekker et al., 2014; Zoefel et al., 2011).

Nevertheless, one study previously reported significant changes in the full EEG-Alpha band following a single NFB session involving alpha-*desynchronizaton* training (Ros et al., 2013), and others have reported successful single session training of the alpha rythym as well (Bazanova et al., 2007; Hanslmayr et al., 2005). However, certain methodological differences

between these studies and ours should be noted. For example, Bazanova et al. (2007) implemented an Alpha-NFB protocol that concurrently involved electromyographic (EMG) biofeedback training for muscle relaxation. Although significant increases in alpha amplitude were seen after just one session of Alpha-NFB/EMG-Biofeedback training, this cannot be unequivocally attributed to NFB training of the alpha rhythm alone. The most salient feature distinguishing the NFB paradigm used in our study from others is that of an eyes-closed vs. eyes-open NFB training protocol, where these previous single-session studies have used the latter condition. The alpha amplitude is normally seen as a function of reduced sensory input from the thalamic nuclei to the cortex (Vernon et al., 2009). Keeping the eyes open will naturally increase sensory input and thus suppress alpha amplitude by default. Therefore, NFB training with eyes open provides a lower baseline from which to attempt to increase the alpha amplitude and as such may be more amenable to positive effects from NFB. In contrast, alpha amplitude at parietal-occipital regions, where NFB training is typically conducted, is greater when eyes are closed. Aware of such considerations, we nevertheless elected to conduct NFB with eyes-closed to insure comparability with MM which is most often practiced with eyes-closed. Despite this we acknowledge that training the enhancement of EEG-Alpha during an eyes-closed condition may be more challenging and require multiple sessions to be successful.

Combining the within-group effects of the two active interventions, MM and Alpha-NFB, they were indeed found to exhibit different results from those seen in the Sham-NFB group. Specifically, whereas MM and NFB exhibited significant *increases* in full band alpha amplitudes, significant *decreases* in amplitude were seen in the sham group. Whereas MM was seen to increase alpha amplitude specifically in the frontal lobe, perhaps as a function of internalized attentional processes, and Alpha-NFB increased alpha amplitude in the posterior lobe perhaps due to the direct self-regulation of alpha activity, participants randomized to Sham-NFB control presumably evidenced neither of these processes and subsequently displayed opposite changes in EEG-alpha amplitude. However, the fact that only significant *within* group differences were found without associated *between* group effects emphasizes the need for either additional sessions or larger samples in future studies.

4.2 Modulation of the Lower (8-10Hz) and Upper (10-12Hz) EEG-Alpha Sub-Bands

The principle rationale underlying the investigation of changes specific to the separate lower (8-10 Hz) and upper (10-12 Hz) alpha sub-bands between each group was to help elucidate the underlying neurocognitive and neurophysiological processes that mediate each of the respective interventions. This would help begin to apply existing literature describing distinct cognitive functions associated with each alpha sub-band to understanding the practice and effects of MM and alpha-NFB. Whereas desynchronization in the lower band is considered to involve neurocognitive processes such as alertness, vigilance and selective attention, upper band desynchronization is involved in neurocognitive processing specific to internalized attention such as required by semantic and working memory processes (Klimesch 1999, 2007). Similar to the full alpha band, between group differences were not found for either of the alpha sub-bands.

However, within group changes in alpha amplitude varied depending on group, and in a way strikingly different from the effects observed for the full alpha band. Consistent with the desynchronization of the lower sub-band during vigilance and selective attention processing, a significant *desynchronization* of the *lower* (8-10Hz) alpha sub-band was seen after the first 3-minute period (1-3 minutes) and after the third 3-minute period (7-9 minutes). This may be reflective of the attentional processes active during MM training which require the practitioner to maintain a consistent state of alertness and vigilance towards distractions as well as an ability to selectively attend to only a subset of possible sensory inputs (i.e. sensations of the breath) while ignoring others (i.e., distractions associated with mind wandering). Additionally, this decrease was seen across all frontal electrode regions, perhaps relating to top-down executive processes important for attentional control. A similar desynchronization in the *upper* (10-12Hz) sub-band, typically seen during performance of semantic and working memory tasks, was present throughout the MM intervention. This may suggest that during the MM training process, participants activate cognitive processes that are typically present during semantic and working memory tasks such as executive attention, which may produce the typical *upper* sub-band ERD. However, this desynchronization was brief, as it only occurred after the initial 3-minutes of intervention. Although MM practice does not explicitly involve working memory processes, this brief desynchronization may provide a basis for understanding the results of numerous studies

documenting the improvements in working memory capacity after MM training (Chambers et al., 2008; Zeidan et al., 2010). Independent of the psychological significance, the fact that opposite findings were observed for the full alpha vs. sub-bands is intriguing. This finding was not expected and to our knowledge the first such report as a description of the neurophysiology of MM. Given recent neurophysiological considerations of alpha oscillatory behaviour, our interpretation of this phenomenon is as follows. The opposing behaviour of *synchronization* across the full-alpha band and *desynchronization* over the two sub-bands occurred during separate time periods across the 15-minute intervention. *Synchronization* in alpha amplitude across the whole (8-12Hz) alpha band during MM practice occurred after the fourth (i.e. 10-12minutes) period, whereas the *desynchronization* across the sub-bands occurred after the first and third periods (1-3 and 7-9minutes). The time dynamics of synchronization and desynchronization may be reflective of the cyclic changes between top-down system readiness and subsequent task performance, respectively. During a state of alpha synchronization, millions of cortical neurons within a specific frequency band (e.g. 8-12Hz) oscillate synchronously with the same phase (Klimesch, 1999). Desynchronization occurs when different oscillators within the alpha band are no longer coupled and begin oscillating with different frequencies (e.g. the lower, 8-10Hz, and upper, 10-12Hz alpha sub-bands). These narrower frequency oscillators most likely reflect the synchronous activity of more local cortical or thalamocortical networks associated with specific cognitive processes and are thus termed 'functional' alphas (Basar and Guntekin, 2012; Basar et al., 1997). That is, large scale synchronization of neurons disintegrate to smaller groups with narrower frequency bands that participate in unique cognitive processes, and this reveals itself in alpha sub-band ERDs. However, recall that ERD and ERS are positively correlated, where alpha synchronization provides the best background for task-related ERD (Klimesch, 1999, 2007). Therefore, full-alpha band synchronization may be a reflection of system preparedness, where alpha oscillators are gathered into a united system ready for task-relevant activity. In this way, the alpha sub-band ERD associated with attentional processing is followed by resynchronization of the full-alpha band and possible return to top-down attentional control and readiness to perform a new task. Ultimately, however, the reliability of these results requires replication in multi-session, longitudinal studies of MM practice.

Desynchronizations in the alpha sub-bands were *not* seen during Alpha-NFB training, distinguishing the results of NFB from those of MM. This discrepancy may partly reflect the

instructions given to Alpha-NFB participants to only passively listen to the auditory feedback tones for guidance during training, compared to the explicit attentional instructions given to MM participants. As such, differences in task set between MM and NFB may have resulted in specific desynchronizations of the lower alpha sub-band specific to the MM group. Moreover, it serves to be noted that NFB involved training of the full alpha band rather than the sub-bands; as such, whereas MM as an integrative *cognitive-affective* intervention may induce effects across the narrow EEG alpha frequencies, the effects of NFB may have been more specific to the frequency trained. Somewhat complicating interpretation, the Sham-NFB also exhibited decreases in the lower and upper alpha sub-bands, however this was limited only to the first 3-minutes of intervention. Since the Sham-NFB received auditory feedback irrelevant to their actual brain rhythms, they may have adopted an alternative strategy similar to the MM group such as focusing on a subset of physical sensations. However, these strategies may not have lasted beyond the initial 3-minutes as further desynchronizations in the sub-bands were not seen after this period.

4.3 Intervention effects on Mood

Whereas the primary focus of this study concerned the potential effects of MM and NFB on attentional control, their immediate influence upon self-reported mood state was also investigated. Participants across all three intervention groups reported an improvement in mood as seen in lower self-report scores for total mood disturbance, anger, tension, and confusion, as well as an increase in vigour, after the interventions. These results suggest a common non-specific factor that could be related to the participants performing an ostensibly anxiolytic intervention and feeling some level of perceived success in doing so. Alternatively, the results may simply reflect demand effects or an experience of looking forward to the completion of the experimental procedure. Interestingly, however, the Sham-NFB group and MM group (MM group with only marginal significance) had lower scores on the confusion subscale post-intervention relative to the Alpha-NFB group. This may allude to the previously mentioned methodological challenge in NFB training of enhancing the alpha amplitude beyond an eyes-closed baseline, potentially warranting a higher level of confusion during the intervention. By

comparison, as Sham-NFB participants did not receive real feedback on their alpha rhythms, a placebo effect would seem to parsimoniously account for these findings.

4.4 Attentional Control: The Stroop Task

We replicated the well-known behavioural pattern of facilitation and interference that has been described in Stroop literature. Across all groups, reaction times were faster and accuracy was higher during congruent conditions, relative to incongruent conditions. Additionally, brief MM practice and Alpha-NFB training significantly impacted neuronal event related desynchronization (ERD) related to cognitive processing during the 400-600ms time period following a Stroop trial, typically considered to reflect the behavioural interference effect in the Stroop task (Liotti et al., 2000; Hanslmayr et al., 2008). These changes, however, were not accompanied by related improvements in behavioral performance nor changes on the P300 neurophysiological marker for attentional control.

We found that brief 15-minute interventions of Alpha-NFB and MM affected EEG-Alpha ERD during the Stroop task, where significantly *less* desynchronization across the upper (10-12Hz) alpha sub-band was found in both of these groups, relative to the non-active Sham-NFB control. Full (8-12 Hz) EEG-Alpha rhythm enhancement is purported to be a common neurophysiological mechanism underlying both of these active interventions. As reported earlier, within-group changes across the 15-minute intervention for both MM and NFB indeed showed significant *increases* EEG-Alpha amplitudes over the full 8-12Hz alpha band. However, *decreases* were observed for EEG-Alpha amplitudes of the lower (8-10 Hz) and upper (10-12 Hz) sub-bands within the MM group specifically. As such, reduction in ERD during the Stroop task could be a consequence of full band EEG-Alpha amplitude enhancement seen in both interventions, relative to the Sham-NFB control. However, no differences in EEG-Alpha change were seen between the active intervention groups.

Moreover, the *reduction* in ERD seen in both MM and NFB was contrary to what we expected, as ERD is typically seen to positively correlate with cognitive performance (Klimesch, 1999, 2007). ERD is usually viewed as a correlate of increased cellular excitability in thalamocortical systems during cortical information processing (Pfurtscheller and Lopes da Silva, 1999). In this context, previous studies have interpreted reductions in ERD as decreased

cognitive effort (Pfurtscheller and Lopes da Silva, 1999; Romero et al., 2008). Since the reduction in ERD for MM and Alpha-NFB groups occurred in the upper alpha band only, this could possibly reflect a reduction in effort needed by these participants to engage in Stroop task-specific cognitive processing. Moreover, it cannot be said that participants in the active interventions were not performing the task suitably, because MM and NFB participants did not exhibit poorer behavioural performance on the Stroop task, where measures were largely equivalent between all groups. Therefore, following previous interpretations expressed in the literature, less cognitive effort in MM and Alpha-NFB participants may have been required in order to perform at the same level as controls. To corroborate such an interpretation, future studies will have to administer cognitive tasks with a greater sensitivity to performance-linked changes in EEG parameters.

It is worthwhile to note that in the framework of MM studies, our findings are in line with a study by Lutz et al. (2009), who also showed a reduction in ERD for MM practitioners during a selective attention dichotic listening task, relative to controls. The reduced ERD was again interpreted as indicative of correspondingly reduced cognitive effort, effected via more efficient brain resource allocation, also correlated with MM training (Slagter et al., 2007).

Such effects have also been shown in multiple studies through reduced P300 amplitudes during cognitive tasks in MM practitioners. For example, reduced P300 amplitudes were seen in MM practitioners, relative to controls, when processing incongruent stimuli during the Stroop task (Moore et al., 2012), during distractor tones in an auditory oddball task (Cahn and Polich, 2009), as well as during an attentional blink task (Slagter et al., 2007). Although a trend towards lower P300 amplitude was found in the Alpha-NFB group, relative to MM and Sham-NFB, no significant differences in P300 amplitude were found in the current study despite finding lower ERD levels in both active MM and NFB interventions. Again, multiple training sessions may be required before any observable effects on the P300 amplitude can arise. Indeed, most of the previously mentioned studies sampled participants after multiple sessions of MM training. It remains promising that the Alpha-NFB group exhibited similar improvements in neurophysiological measures of cognitive effort and attentional resource allocation typically seen after MM training. Taken together, the EEG-Alpha rhythm could be a plausible mechanism by which attentional control is improved through more efficient attentional resource allocation and subsequently reduced cognitive effort exerted during tasks.

Finally, a majority of EEG studies of the Stroop task describe specific time periods that correlate with different cognitive processes used during the stimulus response of a Stroop task. The 400-600ms time period post-stimulus is usually correlated with the behavioural Stroop interference effect. This comes from ERP literature on the Stroop tasks that focus on later ERP components that start around 400ms, as they correlate most strongly with behavioural performance and the Stroop interference effect (Liotti et al., 2000). Similarly, the earlier 200-400ms time period contains the P300 component, which appears to reflect earlier aspects of stimulus processing that, in themselves, however, are *not* thought to be primary sources of the Stroop interference effect per se (Ilan and Polich, 1999). As such, we decided to observe ERD patterns across both time periods. As the reductions in ERD seen across the active interventions occurred across both time periods, MM and Alpha-NFB training may have improved the level of cognitive effort required for both the earlier aspects of stimulus processing as well as later cognitive processing of stimulus interference during incongruent stimuli.

4.5 Limitations and Future Directions

Consideration of the limitations of the current study can assist in providing possible directions for future research regarding Alpha-NFB and MM training for attentional control. First, the sample sizes used in this study were small. Therefore statistical power to detect between group differences, especially among the two active interventions, was decidedly low. Relatedly, the intervention occurred over a single brief 15-minute period of training. This study revealed differences in EEG-Alpha amplitudes between groups that were mostly trending, falling below traditional thresholds for statistical significance in tests of between-group differences; the susceptibility of the present study to Type-2 errors seems large, and replication in larger samples seems advisable. Moreover, we recommend not only single but multiple session, longitudinal designs for observing any long-term changes in EEG-Alpha amplitude after MM versus Alpha-NFB training. This is especially true when considering the intervention difficulty of an eyes-closed Alpha-NFB enhancement training, as well as the unfamiliar conditions of MM in beginners. A future study might compare eyes-open to eyes-closed practices of MM and NFB. In addition, comparison of the outcomes of NFB treatments targeting the full versus lower and upper alpha sub-bands may be fruitful.

The Stroop task in this study was administered using a computerized version with manual button presses used for response. This may have been a limitation to finding behavioural and neurophysiological differences between groups as several authors have highlighted that response formats implemented when administering the Stroop task influence behavioural performance and the sensitivity of interference effects in particular (Kindt et al., 1996; Salo et al., 2001). Specifically, the interference effect of visual-semantic incongruency may be less prominent when manual button presses are used for responses versus verbal communication of responses more typically required in performance of the Stroop task. Although verbal responses are more likely to generate EEG artifacts, Liotti and colleagues (2000) showed that different response formats in the Stroop task (verbal, covert, or button press responses) yield differential scalp distributions of the ERPs.

4.6 Conclusion

This study adds to the growing body of research indicating the role of the EEG-Alpha rhythm in modulating attentional control. Moreover, the positive effects of MM and NFB training on attentional processes were reflected through neural changes associated with performance of a cognitive task, albeit in the absence of differences in behavioural performance. This is, to our knowledge, the first study to directly compare a single session of MM with EEG-Alpha NFB as an effect on neurocognitive performance of the Stroop task, as well as on the lower and upper sub-bands of the EEG alpha rhythm. This study showed that a "low dose" of only 15-minutes of MM and Alpha-NFB training produced observable differences in neurocognitive processing through decreased ERD during the stimulus-response phase of the Stroop task, relative to Sham-NFB controls. Although full band EEG-Alpha enhancement seen during MM and NFB was only significant when observing *within*-group changes, these two active interventions displayed reduced ERD during performance of the Stroop task, relative to the Sham-NFB group, possibly reflecting reduced cognitive effort to obtain equivalent behavioural performance. This further emphasizes the potential role that the EEG-Alpha rhythm may play in improving attentional control through more efficient resource allocation and consequently, reduced cognitive effort, encouraging further study of the therapeutic potential of MM and NFB for improving neurocognition.

Neither differences in EEG-Alpha amplitude nor levels of ERD were different between the two active interventions, however. As such, we cannot make any conclusions regarding the relative benefit of EEG-Alpha NFB for improving cognitive performance beyond the attentional training inherent to MM practice or vice versa. This lack of superiority of EEG Alpha-NFB beyond MM may, nevertheless, be the result of an inadequate dosage of both interventions; more significant differences between the two active interventions may emerge with repeated sessions. Further evaluation of both treatments is required before firm conclusions regarding their relative efficacy can be made.

We conclude that this study provides support for continuing investigation of the therapeutic potential of treatments targeting the EEG-Alpha rhythm, such as MM and NFB, to improve neurocognitive processing. Further evaluation of these two interventions is indicated.

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Zeidan, F., Johnson, S.K., Diamond, B.J., Zhanna, D., & Goolkasian, P. (2010). Mindfulness meditation improves cognition: Evidence of brief mental training. Consciousness and Cognition, 19, 597-605.

Zoefel, B., Huster, R.J., & Herrmann, C.S. (2011). Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance. NeuroImage, 54, 1427–1431.

Curriculum Vitae

Education

2012-Present *University of Western Ontario, London, Ontario*
Masters of Science, Thesis Based
Program: Neuroscience

2003-2010 *University of Toronto, Toronto, Ontario*
Bachelor of Science, Honours
Degree: Neuroscience and Cell Biology Major, Psychology Minor

Professional Experience

Paid Employment

Jan-2014 to April-2014 *Graduate Teaching Assistant*
Professor: Dr. Michael Miller, Department of Psychology, University of Western Ontario
Responsibilities: Assignment evaluation and student office hours extra help

Sept-2013 to Dec-2013 *Graduate Teaching Assistant*
Professor: Sarah Stanton, Department of Psychology, University of Western Ontario
Responsibilities: Essay and discussion board evaluation, student office hours

Sept-2012 to April-2013 *Graduate Teaching Assistant*
Professor: Patrick Brown, Department of Psychology, University of Western Ontario
Responsibilities: Essay and examination evaluation, student office hours

Sept-2011 to May-2012 *Woodbine Steeles Sleep Clinic*
Title: Sleep Technician Volunteer
Operations manager: Ms. Joy Fang
Responsibilities: Collection and analyses of patient information (e.g. medical history, physiological/mental status, etc.), analyses and polysomnograph data entry (apnea hypopnea index, sleep efficiency, arousal index)

Sept-2006 to Sept-2012 *Dr. Edward Chow and Associates, Optometric Clinic and Orthokeratology*
Title: Clinical technician
Responsibilities: Administrative duties, pre-examination vision tests, patient medical history and explanation of examination procedure with patients.

May-2004 to August-2005 *Molecular Genetics Lab, Hospital for Sick Children*
Title: Cytogenetics karyotyper
Team leader: Chin Ho
Responsibilities: Karyotyping of patient chromosomes and marking for possible genetic abnormalities

Medical and Health Science Observerships

Sept-2012 to August-2013 — *Neuropsychiatry, University Hospital*
Supervisor: Dr. Mischa Tursich
Experience: Observation and assessment of patients with psychological trauma

June-2010 to August-2011 — *Otolaryngology, Toronto North Medical Arts Centre*
Supervisor: Dr. Jamil Asaria, Dr. Raymond Ng, Dr. Bosco Lui
Experience: clinical and surgical rotations, patient examinations

July-2010 — *Opthalmology, Bochner Eye Institute*
Supervisor: Dr. Raymond Stein, Dr. Albert Cheskes
Experience: surgical rotation, cataract and laser eye surgery

Research Experience

June-2010 to Present — *Toronto North Medical Arts Centre – Sleep Medicine and Otolaryngology*
Research assistant to Dr. Raymond Ng
Project Responsibilities: Statistical analyses of clinical data, data collections and pre-processing, poster preparation and conference presentations, literature review and summary of projects

Sept-2012 to Present — *University Hospital, London Health Science Centre - Neuropsychiatry*
Graduate research assistant to Dr. Ruth Lanius
Project Responsibilities: Clinical research design for patients with psychological trauma, design of cognitive tasks and Neurofeedback therapy set-up.

Sept-2012 to Present — *University Hospital, London Health Science Centre – Clinical Psychology*
Graduate student to Dr. Paul Frewen
Project Responsibilities: Co-supervision of undergraduate honour's thesis projects, peer review of manuscripts for textbook publications and primary papers.

Sept-2012 to Present — *Dr. Edward Chow and Associates – Optometry and Orthokeratology*
Research assistant
Project responsibilities: Designing and organization of poster and oral presentations, literature review.

Volunteer and Community Service

Aug-2012 — *Dragon Foundation – Young Chinese Leaders Forum*
Position: International Youth Leader, Representative of Canada
Project: Innovation and development in Tianjin, Manifestation of China's 12^{th} 5 year plan

Mar-2011 to Aug-2011 — *Canadian Blood Services – One Match*
Position: Chinese stem cell initiative volunteer
Responsibilities: stem cell donation outreach and awareness in Chinese

community centres, donor cheek cell swabbing, donor questionnaire

2003-2004 *University of Toronto – Innis Residence*
Position: Community Service Co-Chair
Responsibilities: Fundraising, organization of soup kitchen, residence wide events and outreach awareness

Sept-2002 to June-2003 *The Crescent School*
Position: Head Community Service Representative
Responsibilities: Organization and development of community service events, awareness and charity donations for whole school.

June-2001 to Aug-2001 *Bloorview MacMillan Children's Centre*
Position: Student volunteer
Responsibilities: Therapeutic recreation for clients involved in variety of mental disabilities.

Poster and Oral Presentations

Graduate Student (M.Sc.) in Neuropsychiatry

Chow, T.R., Javan, T., Frewen, P.A. (2014 June). Mindfulness meditation versus EEG Alpha Neurofeedback in anxiety and stress reduction: the mediating role of alpha power. *Schulich Department of Psychiatry Research Day*, Oral Presentation. London, Canada.

Chow, T.R., Javan, T., Frewen, P.A. (2014 June). Mindfulness meditation versus EEG Alpha Neurofeedback in anxiety and stress reduction: the mediating role of alpha power. *Canadian Psychological Association Conference*, Oral Presentation. Vancouver, Canada.

Chow, T.R., Javan, T., Frewen, P.A. (2014 March). Mindfulness meditation versus EEG Alpha Neurofeedback in anxiety and stress reduction: the mediating role of alpha power. *London Health Research Day*, Poster Presentation. London, Canada.

Chow, T.R., Javan, T., Frewen, P.A. (2013 June). Mindfulness meditation versus EEG Alpha Neurofeedback in anxiety and stress reduction: the mediating role of alpha power. *Canadian Psychological Association Conference*, Poster Presentation. Vancouver, Canada.

Chow, T.R., Javan, T., Frewen, P.A. (2013 June). Mindfulness meditation versus EEG Alpha Neurofeedback in anxiety and stress reduction: the mediating role of alpha power. *Schulich Department of Psychiatry Research Day*, Poster Presentation. London, Canada.

Chow, T.R., Javan, T., Frewen, P.A. (2013 June). Mindfulness meditation versus EEG Alpha Neurofeedback in anxiety and stress reduction: the mediating role of alpha power. *Canadian Psychological Association Annual Conference*, Poster Presentation. Quebec City, Canada.

Logie-Hagan, K., **Chow, T.R.**, Javan, T., Frewen, P.A. (2013 May). Mindfulness vs. metta meditation: effects on self-other-referential processing. *International Conference on*

Mindfulness, American Health and Wellness Institute. Rome, Italy.

Lai, C., **Chow, T.R.**, Javan, T., Frewen, P.A. (2013 May). A Comparison of the Attentional Effects of Meditation and Fp-HEG Neurofeedback. *International Conference on Mindfulness*, American Health and Wellness Institute. Rome, Italy.

Chow, T.R., Javan, T., Frewen, P.A. (2013 March). Mindfulness meditation versus EEG Alpha Neurofeedback in anxiety and stress reduction: the mediating role of alpha power. *London Health Research Day*, Poster Presentation. London, Canada.

Research Assistant in Sleep Medicine

Ng, R.W, **Chow, T.R.**, Fang, J. (2014 June). Continuous positive airway pressure compliance: effects of trial period and apnea hypopnea index. *American Academy of Sleep Medicine Conference*, Poster Presentation.

Ng, R.W., **Chow, T.R.**, Fang, J. (2013 June). The Effect of Upper Airway Surgery on Sleep Quality and Obstructive Sleep Apnea. *American Academy of Sleep Medicine Conference*, Poster Presentation. Baltimore, U.S.A.

Ng, R.W., **Chow, T.R.**, Fang, J. (2012 June). Relationship between ethnicity and obstructive sleep apnea: OSA in Toronto Chinese population. *American Academy of Sleep Medicine Conference*, Poster Presentation. Boston, U.S.A.

Ng, R.W., **Chow, T.R.**, Fang, J. (2012 June). Effect of thyroid cancer on sleep pattern and obstructive sleep apnea. *American Academy of Sleep Medicine Conference*, Poster Presentation. Boston, U.S.A.

Awards

International Symposium for Contemplative Studies Scholarship Mind and Life Institute, *July 2014*
Western Graduate Research Scholarship, University of Western Ontario, *2012-2014*
Lawson Internal Research Fund Competition, Lawson Health Science Centre, *2013*
Youth Representative of Canada, Dragon Foundation, *2012*
Community Service Award, The Crescent School, *2003*
Community Service Prefect, The Crescent School, *2003*