MINDFULNESS AND COGNITIVE CONTROL

MINDFULNESS AND COGNITIVE CONTROL: EXAMINING THE CONVERGENCE OF TWO CONSTRUCTS

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Doctorate of Philosophy Degree

McMaster University

McMaster University DOCTOR OF PHILOSOPHY (2022) Hamilton, Ontario

(Psychology, Neuroscience & Behaviour)

TITLE: Mindfulness and Cognitive Control: Examining the Convergence of Two Constructs

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NUMBER OF PAGES: xx, 249

Lay Abstract

Mindfulness is a way of paying attention, on purpose, in the present-moment and nonjudgmentally. By focusing attention on present goals and redirecting attention from distractions, mindfulness enhances moment-to-moment awareness of fluctuations in cognitive demands. As a result, meditators can develop greater control over a set of cognitive processes that promote useful behavioural responses. This deliberate practice overlaps with a construct known as “cognitive control”—a set of cognitive processes that facilitate information processing and behaviour to vary adaptively from moment to moment depending on current goals. This dissertation examines the relationship between mindfulness and cognitive control using electroencephalography (EEG) to record ongoing brain activity during two variations of a cognitive control task designed to manipulate difficulty. The results show that self-reported mindfulness predicts cognitive control performance when task difficulty is increased and that two weeks of daily mindfulness training leads to changes in neural activity underlying this cognitive control performance.

Abstract

Mindfulness and cognitive control are overlapping constructs. Mindfulness involves maintaining awareness of the current experience by sustaining attention to relevant information and disengaging from irrelevant information. Cognitive control refers to the set of processes involved in selecting and monitoring information relevant to our goals, while ignoring or inhibiting information irrelevant to these goals. This dissertation contains three studies that examine the convergence between mindfulness and cognitive control. The first study examined the relationship between self-reported mindfulness and behavioural correlates of cognitive control using the Digit Stroop task within two experimental contexts: when task difficulty was not manipulated (non-titrated) and when task difficulty was increased (titrated). The results demonstrate that self-reported mindfulness predicted behavioural performance, but only when cognitive control processes were sufficiently challenged by increasing task difficulty. The second study examined the precise neural mechanisms underlying the relationship between mindfulness and cognitive control using electroencephalography (EEG) to identify changes to event-related potentials (ERPs) during the non-titrated Digit Stroop task after two weeks of daily training. By introducing a novel active control training condition (guided visual imagery meditation) that contrasted passive attention regulation with the focused attention regulation in mindfulness, the results isolated electrophysiological correlates of cognitive control that were uniquely tied to mindfulness training, including increased efficiency in conflict detection, delayed attentional capture by incongruent stimuli, faster conscious evaluation of all stimuli, and delayed automatic detection of all errors. The third study replicated and extended these findings by examining changes to ERPs when the cognitive control system was challenged using the titrated Digit Stroop task. Compared to the active control group, the mindfulness group showed enhanced sensory processing, resistance to stimulus-driven attentional capture and faster conscious evaluation of all stimuli after training. Taken together, this dissertation establishes an empirical relationship between behavioural and electrophysiological correlates of mindfulness and cognitive control.

Acknowledgements

I would like to thank my supervisors, Dr. Heather McNeely and Dr. Margaret McKinnon for their continuous dedication, guidance and support. As an undergraduate Honours thesis student, I had the privilege of being supervised by Dr. Heather McNeely in the Clinical Neuropsychology Services at St. Joseph's Healthcare Hamilton, where I was also mentored by Dr. Margaret McKinnon. To begin and end my graduate research career with two mentors—who not only model excellent scholarship but do so while endorsing and instilling the value of well-being in their students—is seldom observed in academia and something I will appreciate and embrace for a lifetime. I am incredibly grateful for their invaluable feedback, encouragement and moral support. I simply could not have completed this degree without their supervision. I'd also like to take this opportunity to highlight Dr. Heather's McNeely's contribution to the success of my graduate career. From her diligent supervision as my undergraduate Honours thesis supervisor to her consistent conceptual and editorial contributions to this doctoral dissertation—I am so grateful to have come full circle under your supervision and thankful you agreed to take me on as an undergraduate student many years ago, when mindfulness research was still in its infancy. Thank you for your continual support and commitment after all of these years. I would also like to thank my committee member Dr. Brenda Key for providing valuable feedback and guidance on my thesis. Together, Dr. Heather McNeely, Dr. Margaret McKinnon and Dr. Brenda Key served as an incredibly supportive PhD supervisory committee, providing continual guidance, feedback and encouragement throughout the end of my PhD career.

To the countless members of the PNB, McMaster and Hamilton community who have had an indelible impact on my undergraduate and graduate career—thank you for creating such a diverse network of friendship, support and encouragement. From various friends, lab mates, fellow graduate students, undergraduate research students, and post-doctoral fellows to faculty mentors, collaborators and various members of the university administration and support staff—I am grateful for each person who played a significant role in my academic journey and will cherish these memories and lessons for a lifetime.

Finally, I'd like to thank my devoted family for their unconditional love, support, and encouragement. To my father, Muthuswamy Krishnamoorthy, who embodies the values of hard-work, grit, and endurance with incredible grace and optimism—thank you for instilling those values in me and overcoming incredible odds to create a life of opportunity for me. I am so grateful to have a father who passionately believes in me and goes to great lengths to invest in my potential and the actualization of all my goals and dreams. To my mother, Subadhra Krishnamoorthy, who sacrifices everything for her family—thank you for your unconditional emotional support, your unwavering faith in me and always empowering me to navigate every challenge with strength, courage, perseverance, and resilience. I am so lucky to have such a generous, loving, compassionate, and gifted mother who taught me how to listen to my inner voice, trust my intuition, and live unapologetically as the truest, most authentic version of myself. To my older brother, Dr. Subhash Krishnamoorthy, who forged a path of inspiration and brilliance as an assistant professor of surgery and critical care medicine at Columbia University—thank you for motivating me, encouraging me, and always looking out for me. I'm so proud to have a big brother who models excellence, integrity and compassion with such humility, character, and lightheartedness. I will spend a lifetime looking up to you (literally and figuratively).

Learning to straddle the paradox of western science and eastern philosophy while navigating the many challenges of academia has created a series of opportunities to embody the very thing that I study—the science and practice of mindfulness. While my training as a PhD candidate focused on the *science* of mindfulness, the success of my graduate career has relied almost exclusively on the *practice* of mindfulness, particularly in overcoming the many intersectional barriers of academia. This doctoral dissertation is dedicated to the endless network of support and inspiration who have given me the tools, vision and purpose to pursue a PhD in contemplative science, forging a deep, enduring and lifelong commitment to both the science and the practice of mindfulness.

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Chapter 4—The Impact of Mindfulness Training on Electrophysiological Indices of Cognitive Control When Task Difficulty is Increased

Declaration of Academic Achievement

This dissertation contains three studies that aim to expand the literature on mindfulness and cognitive control. I am the first author on all three studies, which will be submitted for publication. All three studies have been in collaboration with my current supervisors, Dr. Heather McNeely and Dr. Margaret McKinnon, as well as my former supervisor and collaborator, Dr. Judith Shedden, and her former post-doctoral fellow, Dr. John Grundy.

Chapter Two establishes an empirical relationship between the construct of dispositional mindfulness and behavioural indices of the Digit Stroop task within two experimental contexts: when task difficulty was not manipulated (non-titrated) and when task difficulty was increased (titrated). This task was conceptualized by Dr. Judith Shedden, who programmed the original task. Undergraduate research assistant, Dominika Bhatia (whom I trained and supervised), helped collect the data. With guidance from Dr. John Grundy and Dr. Judith Shedden, I was responsible for manipulating the programming code, developing the hypotheses and design of the experiment as well as computing all data analysis. I wrote the introduction, methods, results and discussion of this manuscript and created all figures and tables. Both Dr. Heather McNeely and I edited and revised the first draft of the manuscript. All co-authors, including Dr. Margaret McKinnon, Dr. Brenda Key and Dr. Judith Shedden, commented on subsequent versions of the manuscript before reading and approving the final manuscript.

Chapter Three involves using EEG and ERPs to identify precise neural mechanisms underlying the empirical relationship between mindfulness and cognitive control by introducing a novel active control training condition (guided visual imagery meditation) that contrasts passive attention regulation with the focused attention regulation in mindfulness meditation. In doing so, I examine changes to stimulus-locked and response-locked ERPs during the non-modified Digit Stroop task after two weeks of daily training. This task was conceptualized and originally programmed by Dr. Judith Shedden. Undergraduate Honours thesis students, Dominika Bhatia and Soumya Saini (whom I trained and supervised), helped manage participant enrolment, organize training sessions and collect the EEG data. With guidance from Dr. John Grundy and Dr. Judith Shedden, I was responsible for manipulating the programming code, developing the hypotheses and design of the experiment as well as identifying and extracting the ERP components and computing all data analysis. Research assistant, Joey Legere, assisted in programming MATLAB and SHARCNET for EEG data analysis. I wrote the introduction, methods, results and discussion of the manuscript and created all figures. Both Dr. Heather McNeely and I edited and revised the manuscript.

Chapter Four sought to replicate and extend the findings from Chapter Three and examine changes to these electrophysiological indices of cognitive control when the cognitive control system is challenged by increasing task difficulty using the titrated Digit Stroop task. This task was conceptualized and originally programmed by Dr. Judith Shedden. Undergraduate Honours thesis students, Dominika Bhatia and Soumya Saini (whom I trained and supervised), helped manage participant enrolment, organize training sessions and collect the EEG data. With guidance from Dr. John Grundy and Dr. Judith Shedden, I was responsible for manipulating the programming code, developing the hypotheses and design of the experiment as well as identifying and extracting ERPs and computing all data analysis. Research assistant, Joey Legere, assisted in programming MATLAB and SHARCNET for EEG data analysis. I wrote the introduction, methods, results, and discussion of the manuscript and created all figures. Both Dr. Heather McNeely and I edited and revised the manuscript.

All of my former and current committee members, including Dr. Scott Watter, Dr. Bruce Milliken, Dr. Karin Humphreys, Dr. Margaret McKinnon and Dr. Brenda Key, have provided valuable feedback on all three studies within this dissertation.

Chapter 1—Introduction

Swapna Krishnamoorthy

Thesis Overview

Broadly conceptualized as present-centered and non-judgmental awareness, mindfulness involves maintaining awareness of current moment-to-moment experiences by sustaining attention on relevant information, ignoring or inhibiting irrelevant information, while monitoring and disengaging from any judgment or elaborative processing that arises (Bishop et al., 2004; Kabat-Zinn, 1990). In recent decades, widespread scientific interest in mindfulness has documented various adaptive neurobiological, psychological and behavioural outcomes, furthering our empirical understanding of the construct and its relationship with general cognitive functions, various psychopathologies and diverse facets of mental and physical well-being. As a construct fundamentally concerning attention, an emerging body of literature has explored the convergence (and divergence) between mindfulness and related attentional constructs, such as executive function and cognitive control. While various studies have examined the overlapping relationship between mindfulness and cognitive control, discrepancies in experimental design have led to conflicting evidence on the salutary effects of mindfulness attention regulation on cognitive control performance. Furthermore, the precise neural mechanisms underlying these effects are not very well understood. The principal aim of this doctoral thesis is to investigate the effects of mindful attention regulation on behavioural and neural correlates of cognitive control using the high-temporal resolution of event-related potentials (ERPs) extracted from continuous electroencephalogram (EEG) recorded during two variations of the Stroop-interference paradigm designed to vary demands on cognitive control. This chapter will provide an introduction to the thesis by first discussing the background and context, followed by the research problems, the research aims, the significance of this research and finally, its limitations.

Background and Context

During daily activities, we must alter our thoughts and behaviour adaptively from moment to moment in order to meet the cognitive demands of current goals. By focusing attention on present goals and re-directing attention from distractions, mindfulness training enhances monitoring of moment-to-moment fluctuations in cognitive demands. As a result, meditators can develop greater control over a set of cognitive processes that promote useful behavioural adaptations. Although modern scientific inquiry of mindfulness is relatively recent, the deliberate exercise of mindful attention regulation has been practiced for over 2,500 years as a way to observe and gain insight into ongoing events and experiences. Because mindfulness involves successfully sustaining, monitoring and regulating attention, an emerging body of literature has explored the relationship between mindfulness and related cognitive constructs, such as executive function and cognitive control.

Both executive function and cognitive control are often used synonymously, as core regulatory processes that optimize goal-directed behaviours by overriding automaticity (Friedman & Robbins, 2022; Schneider & Shiffrin, 1977). While executive function is a broader notion that has roots in the field of clinical neuropsychology and encompasses a number of cognitive processes reliant on various frontally mediated neural networks, cognitive control is a term derived from studies in cognitive neuroscience and has been associated with a network of neural activity primarily involving the prefrontal cortex (PFC) and related regions such as the cingulate cortex (Miller & Cohen, 2001; Carter et al., 1998). In this thesis, the term cognitive control is used to refer to a set of executive processes that select and successfully monitor information relevant to current goals while ignoring or inhibiting irrelevant information, facilitating information processing and behaviour to vary adaptively from moment to moment depending on those chosen goals (Botvinick et al., 2001; Cohen et al., 2000; Morton et al., 2011; Posner et al., 2004).

A seminal account of cognitive control by Miller and Cohen (2001) proposed that goals and the means to achieve them are represented by the active maintenance of patterned activity in the PFC. These patterns of neural activation in the PFC provide signals to other brain structures that guide neural pathways of information processing to successfully map the inputs, internal states, and outputs needed to perform a given task (Miller & Cohen, 2001). In the face of cognitive interference or conflict between streams of information, the role of the PFC involves the contextual biasing of attention to resolve conflict and exert attentional control. For example, in the classic Stroop-interference paradigm (Stroop, 1935; MacLeod, 1991), participants are presented with a colour word and asked to correctly name the colour of the ink the word is printed in, while ignoring or inhibiting the prepotent tendency to read and name the word itself. In incongruent conditions, where the colour of the ink (e.g., green) is incompatible or in conflict with the meaning of the word (e.g., RED), the prepotency of word-reading over naming the ink colour causes cognitive interference, resulting in delayed decisional latency that is resolved by focusing or biasing attention on the colour of the ink. In turn, this interference leads to activation of the anterior cingulate cortex (ACC), which detects conflict, and is accompanied by activations of the dorsolateral (dl)PFC, which resolves conflict by mediating top-down adjustments of response control (Carter et al., 1998; Kerns et al., 2005). According to this theoretical model of cognitive control, the ACC detects conflict that is resolved by the top-down attentional control and contextual biasing of response options from the dlPFC (Miller & Cohen, 2001).

Miyake and colleagues (2000) further organized cognitive control processes into three key constructs: inhibition of prepotent responses (stopping an automatic response, sometimes in order to make an alternative response), updating working memory (continuously replacing information that is no longer relevant in working memory with newly relevant information observed in the environment), and shifting attention (switching between two alternative tasks). Taken together, these core cognitive control abilities mediate goal-oriented behaviour by inhibiting irrelevant automatic impulses or responses, dynamically updating working memory with relevant information, and shifting attention as necessary, depending on the demands of current goals. Such performance monitoring relates directly to the cultivation of mindfulness, as deliberate mindful practice requires maintaining meta-cognitive awareness of the current experience by sustaining attention on relevant information (e.g., focusing on sensations of the breath), ignoring or inhibiting prepotent impulses (e.g., resisting rumination or mind-wandering), while updating working memory with relevant information (e.g., observing thoughts, emotions or sensations of the breath as they arise) and switching attention (e.g., disengaging from any elaborative processing or judgment of internal or external distractions and redirecting attention back to the sensations of the breath). By regulating attention in this manner, mindfulness practice is an ideal vehicle for the cultivation of cognitive control.

Accordingly, a wealth of studies has examined the impact of mindfulness on various measures of cognitive control. The most consistent findings belong to behavioural studies that examined conflict resolution using stimuli that present competing streams of information, such as the Stroop task (e.g., Allen et al., 2012; Chan & Woollacot, 2007; Moore & Malinowski, 2009; Teper & Inzlicht, 2013; Wenk-Sormaz, 2005). Other mindfulness studies have also found enhanced cognitive control performance on tasks such as the Attention Network Test (ANT; Fan et al., 2002; Jha et al., 2007; Tang et al., 2007), an Internal Switching Task (Chambers et al., 2008) and the Continuous Performance Task (CPT; Rosvold et al., 1956; Semple, 2010; Servan-

Schreiber et al., 1996). However, other studies using similar behavioural paradigms showed little to no effect of mindfulness on measures of executive function (*Stroop*: Anderson et al., 2007; Josefsson & Broberg, 2011; Moore et al., 2012; Polak, 2009; Semple, 2010; *Flanker*: Larson et al., 2013; *ANT*: Polak, 2009), leading to cautious interpretations on the salutary effects of mindfulness on cognitive control.

More recently, an emerging body of literature has used the high-temporal resolution of event related potentials (ERPs) extracted from electroencephalogram (EEG) recordings of brain activity arising continuously during task performance to disentangle discrepant findings by examining the neural underpinnings of mindfulness and cognitive control. In the cognitive electrophysiology literature, the most reliable ERP markers of executive attention and cognitive control include the N2, P3a, P3b, ERN and Pe components. The N2, P3a and P3b waveforms are examples of stimulus-locked ERP components that are time-locked to the onset of stimulus presentation during a task. The ERN and Pe waveforms are examples of response-locked ERP components that are time-locked to the onset of response completion during a task. While the amplitude of ERP components indexes the allocation of resources to particular processing that is unfolding, the latency of the waveform signals the speed of processing.

The N2 is a negative deflection that is observed 200 to 400 ms post-stimulus in anterior regions and is considered an index of conflict monitoring and inhibition (Bruin et al., 2001; Donkers & Van Boxtel, 2004; Folstein & Van Petten, 2008; Nieuwenhuis et al, 2003;). Mindfulness has mainly been associated with increased N2 amplitudes during various cognitive control tasks, suggesting enhanced conflict detection and monitoring as well as inhibitory suppression of incorrect responses (*Auditory oddball task*: Atchley et al., 2016; *Stroop*: Malinowski et al., 2017; Moore et al., 2012; *ANT*: Norris et al., 2018; *Go/Nogo*: Quaglia et al., 2016). However, at least one study has shown a null effect on N2 modulation after mindfulness training (*Go/Nogo*: Schoenberg et al., 2014).

The P3a is a positive deflection that peaks approximately 300 to 400 ms in anterior regions of the scalp and is thought to reflect unconscious, involuntary or automatic stimulus-driven attention to salient or unexpected events (Bush et al., 2000; Escera et al., 2001; Folstein & Van Petten, 2008; Muller-Gass et al., 2007; Salisbury et al., 2004). Although studies examining the impact of mindfulness on the P3a are very limited, a reduced P3a amplitude was observed during an auditory oddball task in expert Vipassana meditators during a meditative state, suggesting reduced stimulus-driven attentional capture to irrelevant, yet salient stimuli (Cahn & Polich, 2009). This supports the hypothesis that mindfulness facilitates unbiased information processing by disengaging the attentional system from stimulus-driven activation (Verdonk et al., 2020). In contrast, an increased P3a amplitude was observed during an AX-Continuous Performance Task (AX-CPT; Dias et al., 2003; MacDonald, 2008; Servan-Schreiber et al., 1996) after 8 weeks of MBSR training, interpreted as greater inhibition of prepotent responses by reactive (rather than proactive) cognitive control mechanisms (Incagli et al., 2020; Morales et al., 2015).

The P3b is a positivity observed in temporal-parietal scalp regions 300 to 500 ms post-stimulus and is widely considered a signature of conscious access to or conscious processing of a stimulus (Dehaene & Changeux, 2011; Folstein & Van Petten, 2008; Johnson & Donchin, 1980; Polich, 2007). Although some studies show no effect of mindfulness on the P3b (Norris et al., 2018; Malinowski et al., 2017), mindfulness has mainly been associated with increased P3b amplitudes when processing task-relevant stimuli (Atchley et al., 2016; Delgado-Pastor et al., 2013; Smart et al., 2016) and decreased P3b amplitudes when inhibition of task-irrelevant processing was required (Atchley et al., 2016; Howells et al., 2012; Moore et al., 2012; Slagter et al., 2007). This supports the hypothesis that mindfulness modulates the threshold of conscious access to goal-relevant information through attentional amplification (Verdonk et al., 2020).

Finally, the error-related negativity (ERN) and error positivity (Pe) are two of the most reliable neural markers associated with monitoring and evaluating performance, indexing the neural response of cognitive control after an error is committed. The ERN is a negative deflection that is observed within 100 ms in anterior regions of the scalp after error commission and is considered an index of error monitoring and evaluative control (Endrass & Ullsperger, 2014; Falkenstein et al., 2000; Gehring et al., 2012). Following the ERN, the Pe is a positive deflection that peaks around 100 to 200 ms after an error is committed and is thought to reflect motivational significance of errors, reflected by larger amplitudes on trials with conscious awareness of error commission (Logan et al., 2015; Steinhauser & Yeung, 2012). While some studies show an increased ERN associated with mindfulness reflecting greater attention in response to errors (Eichel & Stahl, 2017; Saunders, Rodrigo, & Inzlicht, 2016; Smart & Segalowitz, 2017; Teper & Inzlicht, 2013) other studies show decreased ERN amplitude, or no change, resulting in mixed interpretations (Bing-Canar et al., 2016; Larson et al., 2013; Schoenberg et al., 2014). Likewise, the impact of mindfulness on Pe modulation is unclear, with some studies showing an increased amplitude reflecting greater conscious awareness in response to an error (Schoenberg et al., 2014), some studies showing a decreased amplitude interpreted as attenuated salience or awareness of error commission (Larson et al., 2013) while others showed no change in Pe modulation (Bing-Canar et al., 2016; Saunders et al., 2016; Smart & Segalowitz, 2017; Teper & Inzlicht, 2013).

Although not typically studied in the mindfulness and cognitive control ERP literature, the P1 and N1 components are related to sensory processing in visual cortices and are modulated by focus of attention with scalp distributions located at occipital regions in the hemisphere contralateral to the stimulus location (Ahumada-Mendez et al., 2022; Debruille et al., 2019). The P1 is the first positive ERP component observed 80 to 130 ms post-stimulus and is immediately followed by the N1 component, which is a negative deflection observed 130 to 190 ms post-stimulus (Debruille et al., 2019; Ahumada-Mendez et al., 2022). Although previous research has shown the P1 and N1 are sensitive to spatial and feature-based selective attention (Hillyard & Munte,1984; Mangun, 1995), increased N1 amplitudes have been observed during a Stroop matching task, providing evidence of modulations in early sensory processing during Stroop-like paradigms (David et al., 2011). Furthermore, Moore et al. (2012) compared colour-word Stroop performance after 16 weeks of mindfulness training using a population of healthy younger adults and reported an increased N2 amplitude on incongruent trials. However, their reported increase of a negative deflection that peaked between 160 and 240 ms over occipito-parietal regions of both hemispheres better fits the profile of an N1 component, rather than an N2 component. Although the P1 and N1 are not indices of cognitive control, in light of this evidence, it's plausible that the mindful practice of focusing attention on task-relevant information can enhance early sensory processing sensitive to selective attention, resulting in modulations of P1 and N1 components.

Taken together, the majority of evidence from prior studies shows that mindfulness is associated with enhanced behavioural performance on various tasks involving executive function as well as modulations of ERPs reflecting neural markers of cognitive control processes such as conflict monitoring (N2), automatic allocation of stimulus-driven attention (P3a), conscious stimulus evaluation (P3b), and error processing (ERN and Pe). Moreover, although less extensively studied to date, mindfulness may also influence ERPs related to early sensory processing sensitive to selective attention (P1 and N1).

Research Problem

Studies investigating the salutary effects of mindfulness on behaviour and neural correlates of executive function are increasing, with the majority of evidence establishing a robust relationship between mindfulness and enhanced cognitive control. However, the precise neurocognitive mechanisms underlying this relationship are still unclear and difficult to interpret with such large discrepancies in experimental design between studies. For example, in the current literature, mindfulness is typically operationalized and studied in three different ways: as a state evoked by brief induction usually in novice or naive meditators, as a trait-like training outcome of continued formal practice in experienced meditators, or as an inherent disposition that varies across individuals using self-report measures. While some cross-sectional studies have examined the impact of brief mindfulness induction in naive meditators (Bing-Canar et al., 2016; Larson et al., 2013; Norris et al., 2018; Saunders et al., 2016), other cross-sectional designs have examined the impact of long-term mindfulness practice in experienced meditators (Atchley et al., 2016; Teper & Inzlicht, 2013), characterizing two extremes of mindfulness expertise and their respective impact on cognitive control. Other studies have operationalized mindfulness as an inherent disposition using self-reported psychometric measures, but their interpretations are limited by test validity, reliability and the distribution of responses used to categorize participants into groups of low mindfulness and high mindfulness based on a median split (Quaglia et al., 2016; Eichel et al., 2017).

This discrepancy highlights the value of carefully controlled longitudinal studies that examine hypothesized changes to behavioural and neural correlates of cognitive control before and after a mindfulness intervention using an appropriate control condition to contrast and isolate the unique effects of mindful attention regulation, lacking from most mindfulness studies. While some studies compare mindfulness training with waitlist controls who are not engaging in any training program between testing sessions (Moore et al., 2012; Schoenberg et al., 2014), other studies compare mindfulness training with active control groups who are engaging in various activities ranging from Pilates fitness programs to psychoeducational training and brain training exercises (Incagli et al., 2020; Malinowski et al., 2017; Smart et al., 2017).

Finally, the effects of mindful attention regulation on cognitive control may not be detected unless those underlying cognitive control mechanisms are sufficiently challenged. While a number of studies showed that mindfulness is associated with improved cognitive performance (*Stroop*: Allen et al., 2012; Chan & Wollacott, 2007; Moore & Malinowski, 2009; Teper & Inzlicht, 2013; Wenk-Sormaz, 2005; *ANT*: Jha et al., 2007; Tang et al., 2007), other studies have found little to no behavioural differences after mindfulness training (*Stroop*: Anderson et al., 2007; Josefsson & Broberg, 2011; Moore et al., 2012; Polak, 2009; Semple, 2010; *ANT*: Polak, 2009; *Flanker*: Larson et al., 2013). Without sufficient demands on cognitive control processes, the effects of mindfulness on cognitive control abilities may not be observable, contributing to inconsistent findings and interpretations in the mindfulness literature.

As such, the outcome of behavioural and electrophysiological studies of mindfulness and cognitive control can vary greatly depending on how mindfulness is operationalized within the experimental design, what kind of control condition is used to contrast any mindfulness training, and whether executive function tasks sufficiently challenge the cognitive control processes that are associated with mindful attention regulation. As a result, it is currently difficult to interpret the effects of mindfulness on cognitive control using behavioural and electrophysiological measures without carefully controlled longitudinal designs that include an appropriate control group in order to isolate the cognitive control mechanisms unique to mindful attention regulation and tasks designed to sufficiently challenge demands on cognitive control.

Research Aims and Objectives

The principal aim of this doctoral thesis is to investigate the impact of mindfulness on behavioural and neural correlates of cognitive control in healthy young adults using the high-temporal resolution of EEG to record ongoing brain activity as meditators adapt to varying cognitive demands during two different variations of the Stroop-interference paradigm.

Specifically, there are three main research objectives to achieve the principal aim of this thesis. The first research objective is to examine the overlapping constructs of mindfulness and cognitive control by establishing an empirical relationship between psychometric measures of dispositional mindfulness in a sample of non-meditators using two executive function tasks designed to vary demands on cognitive control. The second research objective is to identify neural markers of cognitive control specifically associated with mindfulness mindful attention regulation training passive attention regulation training. The third research objective is to compare and contrast changes to these neural markers of cognitive control after mindfulness training or active control training when cognitive control processes are sufficiently challenged on a task designed to manipulate difficulty.

Significance

By using the high temporal resolution of electroencephalography to record event-related potentials during variations of a cognitive control task designed to manipulate task difficulty, this thesis examines ongoing brain activity in mindfulness meditators versus appropriate controls as they adapt to varying demands on cognitive control. Compared to the passive attention regulation in the novel active control training condition, the specific practice of sustaining focus, disengaging from distractions and redirecting attention in mindfulness meditation is hypothesized to change neural activity that will be reflected in unique changes to well established ERP markers of executive function and cognitive control. This work will be the first to contrast components of focused attention regulation with components of passive attention regulation to isolate specific effects of the attention regulation unique to mindfulness meditation, particularly when cognitive control processes are sufficiently challenged. Accordingly, this inclusion of a novel active control training will serve as a replication control for the findings of an expansive literature on the salutary effects of mindfulness. The results of this thesis have important implications for our empirical understanding of mindfulness as a psychological construct, the neurocognitive mechanisms involved in mindful attention regulation, and their convergence with well-established mechanisms of executive function and cognitive control. As an accessible and ideal tool for the cultivation of cognitive control, the implications of this program of mindfulness research also have meaningful applications to everyday performance monitoring. By integrating processes of attention regulation, cognitive control and their underlying neural mechanisms to study specific experience-dependent changes, this thesis is vital in broadening the knowledge of fundamental psychological processes involved in the transfer of trained attention via mindfulness to real world performance monitoring.

Limitations

In this thesis, mindfulness is operationalized as an inherent disposition (dispositional mindfulness) that varies across individuals and as a training outcome of short-term daily mindfulness practice. However, the scope of this thesis does not allow for an evaluation of how dispositional mindfulness interacts with changes in behavioural and electrophysiological correlates of cognitive control after two weeks of mindfulness practice. Consequently, a key assumption of this thesis is that mindfulness training influences cognitive control equally across naive meditators, regardless of whether they are high or low in dispositional mindfulness before training. However, the salutary effects of mindfulness training may have more impact or may only be observable in individuals who are low in dispositional mindfulness prior to training.

To completely isolate the effects of mindfulness training on cognitive control, the inclusion of an inactive control condition in addition to an active control condition is necessary to rule out training outcomes that are a result of task practice effects. Due to logistical constraints on time and resources, this thesis does not compare mindfulness training and active control training with an inactive control group that doesn’t engage in any training between pre-test and post-test sessions. Therefore, this research cannot confirm whether the active control condition influences cognitive control processes by virtue of engaging domain general attentional mechanisms.

To constrain the focus of mindfulness on cognitive control, this thesis operationalizes mindfulness in a secular way, focusing on attentional influences involved in mindful attention regulation rather than the affective influences that are associated with the emotional acceptance and nonjudgmental aspects of mindfulness practice. Although manipulating task difficulty may increase motivational and emotional salience during the cognitive control task, this thesis does not directly examine affective or motivational influences on the behavioural and neurophysiological correlates of cognitive control performance. Therefore, the results of this doctoral research do not extend to the emotional acceptance and nonjudgmental facets of mindfulness that are related to emotional and psychological well-being—an essential hallmark and enticing application of mindfulness practice.

Finally, it is important to acknowledge that the construct of mindfulness has been over-secularized in Western science in order to empirically study the relationship between mindfulness and related attentional constructs. Although this thesis examines the effects of mindfulness on cognitive control using a relatively homogenous sample of young, healthy adults with no previous meditation experience, the findings in this program of research may not generalize to children, older adults, clinical populations, or special populations (e.g., expert meditators) who might differ in cognitive control abilities and their engagement with mindfulness practice. Likewise, the findings of this thesis also may not generalize to heterogeneous groups with diverse ethnicities and cultural experiences who may conceptualize mindfulness in non-secular ways. Along the same lines, there are a number of meditative practices that involve components of mindfulness, such as Zen meditation, Transcendental Meditation I, Vipassana meditation, Qigong meditation, Tai Chi, and Yoga with the most diffuse forms derived from Hinduism and Buddhism spiritual traditions (Tomasino et al., 2014). Therefore, it is critical to acknowledge the various ancestries of mindfulness practice to avoid appropriation of non-secular traditions in the pursuit of scientific inquiry.

Outline of Present Research

Chapter One introduces the context of this research, provides the relevant background to understand the research aim, objectives and questions, and discusses the implications as well as the limitations of this doctoral thesis.

Chapter Two examines the empirical relationship between dispositional mindfulness and cognitive control within a population of young adults without any formal mindfulness training.

In this chapter, self-report measures of dispositional or trait mindfulness are used to examine which facets of mindful attention regulation predict behavioural performance on two variations of the Digit Stroop task (variation of the classic Stroop-interference paradigm), designed to manipulate difficulty and vary cognitive control demands thereby increasing sensitivity to mindfulness-related behavioural differences.

Chapter Three introduces a novel active control condition (guided visual imagery meditation) in a carefully controlled longitudinal training study designed to isolate the unique effects of mindfulness training on both stimulus-locked and response-locked electrophysiological indices of cognitive control during the Digit Stroop task. Compared to the passive attention regulation in the guided visual imagery meditation control group, the specific practice of sustaining focus, disengaging from distractions and redirecting attention in mindfulness meditation training is hypothesized to change neural activity that can be captured by unique changes to ERP indices of early sensory processing (P1 and N1), conflict detection (N2), stimulus-driven attentional capture (P3a), conscious stimulus evaluation (P3b) and error monitoring (ERN and Pe).

Chapter Four aimed to capture an electrophysiological time course of cognitive control mechanisms associated with mindfulness by examining both stimulus-locked and response-locked ERPs in a mindfulness training group versus the guided visual imagery active training group using a cognitive control task designed to increase difficulty. By manipulating task difficulty and comparing mindfulness training with the same novel active control group using the same sample of participants from the carefully controlled longitudinal design in Chapter Three, this chapter sought to replicate the findings from Chapter Three, while documenting the effects of mindfulness training on ERP markers of executive function when cognitive control is sufficiently challenged.

Chapter Five reviews the research problem and answers the research questions presented in this thesis by summarizing key findings, interpreting main results, and providing a critical analysis of their convergence and divergence with the current mindfulness literature. This chapter also acknowledges the limitations of Chapter Two, Chapter Three, and Chapter Four, while discussing practical applications of main findings, proposing suggestions for future research and providing a concluding summary of the overall thesis.

Chapter 2—Dispositional Mindfulness Predicts Cognitive Control Performance

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Judith M. Shedden

Abstract

Although numerous studies have examined the effects of mindfulness training on cognitive control, it remains unclear whether mindfulness practice always leads to performance benefits. One potential explanation for this discrepancy is that individuals vary in dispositional mindfulness, or the propensity to dwell in mindful states. Many outcome studies, however, do not take dispositional mindfulness into account and therefore cannot rule out the impact of pre-existing differences. Furthermore, effects of mindfulness on cognitive performance may not be observable unless task demands are sufficiently challenging. Here, we use the Mindful Attention Awareness Scale (MAAS) and the Five Facet Mindfulness Questionnaire (FFMQ) to examine whether dispositional mindfulness predicts performance outcomes on two variations of the Digit Stroop task designed to manipulate cognitive control demands. We used regression analyses to assess whether measures of trait mindfulness significantly predicted response times (RT), accuracy, Stroop interference effect, post-error slowing (PES), or sequential congruency effect (SCE). In Experiment 1, where task difficulty was not manipulated, measures of dispositional mindfulness did not predict any indices of cognitive control performance. In Experiment 2, where cognitive control demands were challenged, single linear regression analyses showed that the MAAS significantly predicted a reduced Stroop interference effect, while total FFMQ significantly predicted a smaller Stroop interference effect and accuracy on incongruent trials. Multiple linear regression analyses of the FFMQ facets revealed that only the *Nonreactivity to Inner Experience* facet significantly predicted a smaller Stroop interference effect while the *Observing* facet significantly predicted accuracy on congruent and incongruent trials. These findings suggest that individual differences in dispositional mindfulness predict cognitive control performance, but only when demands on these processes are experimentally challenged.

Introduction

Mindfulness is typically studied in three different ways: as a trait-like outcome of long-term formal practice, as a state evoked by brief practice, or as an inherent disposition that varies across individuals using psychometric measures. Few studies, however, take individual differences in dispositional mindfulness into account before evaluating the outcome of state or trait-dependent changes of mindfulness practice, leading to inconsistent interpretations on the effects of mindfulness practice in the scientific literature. This is important when studying the relation between overlapping constructs like mindfulness and cognitive control, where individual differences in dispositional mindfulness can explain variation in a set of processes measured by behavioural performance on cognitive control tasks. Here, we evaluate how individual differences in dispositional or trait mindfulness predicts performance on two different versions of the Digit Stroop task, designed to vary demands on cognitive control.

Mindfulness and cognitive control are overlapping constructs. Mindfulness— broadly conceptualized as present-centered and non-judgmental awareness—involves maintaining meta-cognitive awareness of the current experience while sustaining attention to task-relevant features and disengaging from elaborative processing of irrelevant information (Kabat-Zinn, J., 1990; Bishop et al., 2004). Cognitive control refers to the set of processes that focus on information relevant to a particular goal while ignoring irrelevant information (Morton et al., 2011). This allows information processing and behaviour to vary adaptively from moment-to-moment depending on these goals (Botvinick et al., 2001; Cohen et al., 2000; Posner et al., 2004). By focusing attention on present goals and re-directing attention from distractions, mindfulness practice can enhance moment-to-moment awareness of fluctuations in cognitive demands. Theoretically, in turn, meditators may develop greater control over a set of cognitive processes that promote useful behavioural adaptations. However, evidence of a robust empirical relationship between mindfulness and cognitive control its relevance for everyday life remains ambiguous.

Although various studies have examined the effects of mindfulness meditation on attention and cognitive control, it remains unclear whether mindfulness training always leads to performance benefits. Whereas some studies show significant improvements on attention and cognitive control measures such as the Stroop task (Stroop, 1935) or the Attention Network Test (ANT; Fan et al., 2002) after mindfulness training, others do not. Numerous studies illustrate mindfulness training is associated with a reduced Stroop interference effect, thus reflecting an enhanced ability to inhibit attention to salient yet task-irrelevant information. Compared to an active control condition, Allen and colleagues (2012) found short-term mindfulness training can reduce the Stroop interference effect after two hours of mindfulness training per week for six weeks. Similarly, Wenk-Sormaz (2005) reported 20 minutes of meditation can reduce Stroop effect in meditation naive participants compared to cognitive and resting control groups. A similar effect is observed in experts, where meditation experience is associated with a reduced Stroop interference effect, supporting the influence of long-term mindfulness practice on reducing interference between competing or conflicting channels of information (Chan & Woollacott, 2007; Moore & Malinowski, 2009; Teper & Inzlicht, 2013).

Mindfulness training is also associated with altered performance on the Attention Network Task (ANT), a combination of the cued reaction time (RT) (Posner, 1980) and the flanker task (Eriksen & Eriksen, 1974), which was designed to evaluate three distinct attentional networks: alerting, orienting and executive attention (Fan et al., 2002). The ANT requires participants to determine whether a central target arrow points left or right and efficiency of each network is measured by calculating the influence of alerting cues, spatial cues, or flankers on mean response times (Fan et al., 2002). Specifically, when the central arrow is flanked by two congruent or incongruent arrows, executive attention or conflict monitoring performance is assessed by subtracting mean RT of all congruent trials from the mean RT of all incongruent trials (Fan et al., 2002). Critically, Tang et al. (2007) found that meditation-naive participants who engaged in five days of brief integrative body-mind training (IBMT), a form of mindfulness practice, demonstrated improved conflict monitoring performance on the executive attention network portion of the task compared to an active control group that engaged in progressive relaxation training. In contrast, Jha and colleagues (2007) evaluated ANT performance at two different time points across 3 different groups: 1) a group of meditation naive individuals who completed an 8-week mindfulness-based stress reduction (MBSR) course focused on concentrative meditation skills; 2) a group of individuals experienced with concentrative meditation who participants in a 1-month mindfulness retreat; and 3) an inactive control group who were meditation native and received no mindfulness training. Relative to the MBSR and inactive control groups, the experienced concentrative meditators showed improved conflict monitoring performance at Time 1, reflecting greater executive attention efficiency at baseline. There was, however, no groupwise difference in conflict monitoring performance at Time 2 across all three groups, suggesting an influence of practice effects or a lack of task sensitivity in detecting floor effects of mindfulness training on executive attention over time. Similarly, other studies have found little to no behavioural differences in conflict monitoring performance after mindfulness training (*Stroop*: Anderson et al., 2007; Josefsson & Broberg, 2011; Moore et al., 2012; Polak, 2009; Semple, 2010; *ANT*: Polak, 2009; *Flanker*: Larson et al., 2013).

One potential explanation for this discrepancy is that individuals vary in their inherent ability to sustain and regulate attention mindfully, even without any practice or formal training. This propensity to dwell in mindful states over time is known as trait or dispositional mindfulness and varies across individuals (Brown & Ryan, 2003; Brown et al., 2007; Kiken et al., 2015). Dispositional mindfulness measured by the three most widely used measures, the MAAS (Brown & Ryan, 2003), the Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006) and its predecessor the Kentucky Inventory of Mindfulness Skills (KIMS; Baer et al., 2004), has been shown to correlate with several theoretically meaningful indicators of well-being and psychopathology (see Brown et al., 2007 for review).

Here, higher dispositional mindfulness is associated with cognitive and behavioural flexibility that produces more adaptive than maladaptive responses to events (Jordan et al., 2014; Kim et al., 2011). For example, an emerging body of evidence suggests that the MAAS and FFMQ subscale *Act with Awareness* is moderately correlated with self-reported attentional control (Brown et al., 2013; Quaglia et al., 2016). Along the same lines, FFMQ facets predict performance on visual working memory, temporal order, and conflict monitoring tasks (Anicha et al., 2012) and individual differences on the MAAS predict post-conflict recovery in a task-switching paradigm (Grundy et al., 2018). Accordingly, there is an urgent need to examine dispositional mindfulness as a mediating or moderating factor in training-induced effects. Despite such knowledge, many studies do not take dispositional mindfulness into account when measuring training effects and therefore cannot rule out pre-existing differences in individuals who are more or less prone to be in a mindful state, leading to inconsistent findings across studies. Moreover, any trait or mindfulness-induced state effects may remain undetected unless adequate cognitive control measures are used. Without varying demands on cognitive control, effects of mindfulness on behavioural performance may not be observable, contributing to inconsistencies in the literature.

The current study examines how individual differences in self-reported dispositional or trait mindfulness predict performance on two variations of the Digit Stroop task that vary in cognitive control demands and sensitivity to mindfulness-related behavioural changes. Here, we use the Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003) and the Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006) to examine which measures of dispositional mindfulness predict behavioural performance on a modified Digit Stroop task in two experiments. Experiment 1 consists of 44 subjects who completed an unmodified or "non-titrated" Digit Stroop task (no constraints on accuracy). Experiment 2 consists of 42 subjects who completed a modified or "titrated" Digit Stroop task that was manipulated to increase task difficulty (accuracy maintained at 70-80%; see Figure 1). In both experiments, we used single linear regression analyses to assess whether measures of overall dispositional mindfulness (measured by the MAAS and FFMQ) significantly predicted response times (RT), accuracy, Stroop interference effect, post-error slowing (PES), and sequential congruency effect (SCE). Critically, we only expected to detect this relation in Experiment 2 where the task was manipulated to vary demands on cognitive control. Finally, we also used multiple linear regression analyses to identify which of the facets of dispositional mindfulness measured by the FFMQ (*Observing*, *Describing*, *Act with Awareness*, *Nonjudging of Inner Experience*, and *Nonreactivity to Inner Experience*; Baer et al., 2006) predicted performance on a variation of the Digit Stroop task designed to increase demands on cognitive control. Here, we hypothesized the *Observing* or *Act with Awareness* facets would reflect the ability to sustain and switch attention from trial to trial, predicting response times to congruent and incongruent trials, sequential congruency effects (SCE), as well as the Stroop interference effect. We further hypothesized that the *Nonjudging* or *Nonreactivity* facets would reflect disengagement of elaborative processing, predicting greater accuracy and post-error slowing (PES).

Methods

Experiment 1: Non-Titrated Digit Stroop Task

Participants

Forty-four undergraduate and graduate students were recruited from McMaster University's Department of Psychology, Neuroscience & Behaviour participant pool as part of a longitudinal meditation training study. The exact age of each participant was not collected in this study, but all were under the age of 30 years. All participants also had normal or corrected to normal vision and provided informed consent before participating in the study. All procedures complied with the Canadian Tri-Council Policy on Ethics and were approved by the McMaster Research Ethics Board.

Materials and Apparatus

All stimuli were presented on a Pentium class computer with Presentation® experimental control software (Neuro Behavioural Systems; version 12.2) on a 17-inch CRT monitor with a refresh rate of 85 Hz. The stimuli appeared in black, sans-serif numerals in the center of a grey background. Visual angle of the stimuli ranged from 5° to 6° horizontally between left and right edges of the outermost numbers and from 3° to 4° vertically between upper and lower edges of the outermost numbers. A chinrest was used to maintain a consistent viewing distance of approximately 80 cm between participants. To assess dispositional mindfulness, the Mindfulness Attention Awareness Scale (MAAS; Brown and Ryan 2003) and Five Facet Mindfulness Questionnaire (FFMQ, Baer et al., 2006) were administered.

Procedure

The Digit Stroop task is a variation of the classic Stroop task, used to measure cognitive control and executive attention (Stroop, 1935). Instead of coloured words, the task stimuli were strings of one to six digits presented in the center of a gray screen. All digits in the array had the same identity (1, 2, 3, 4, 5, or 6) and the number of digits presented during each trial varied randomly (from one digit to six digits). The digits were mapped to computer keys along the bottom edge of the keyboard: “z”, “x”, and “c” were used for left-hand responses and represented digits “1”, “2”, and “3” respectively, while “,”, “.”, and “/” were used for right-hand responses and represented digits “4”, “5”, and “6” respectively. Participants were asked to respond as quickly and as accurately as possible by identifying the number of digits in the string, while ignoring the identity of the digits themselves. For example, the correct response to the stimulus, “5 5 5 5” is “4” (since there are 4 digits) and is correctly executed by pressing the corresponding “,” key. The stimulus set consisted of equal congruent and incongruent trials. On congruent trials, the string length matched the identity of the digit presented (e.g., the correct answer to “6 6 6 6 6 6” is “6”). On incongruent trials, the string length did not match the digit identity (e.g., the correct answer to “3 3” is “2”). In between trials, a fixation cross (+) was displayed at the center of the screen for an inter-trial interval (ITI) that varied randomly from 400 to 800 milliseconds (ms). On each trial, the stimulus duration randomly varied from 800 to 1200 ms for the entire experiment. The task consisted of 540 trials in total (50% congruent, 50% incongruent), presented in ten blocks of 54 trials with brief breaks between each experimental block. The experiment was conducted as part of a series of baseline measures in a larger, longitudinal meditation training study. This portion of the experiment was conducted in less than an hour. Participants were provided with informed consent following verbal and written explanation of the experiment. All participants completed the Digit Stroop task before completing electronic versions of the self-report measures to avoid any influence of mindfulness items on task performance. After completing the experiment, participants received research participation credit and a debriefing information sheet that summarized the details of the study.

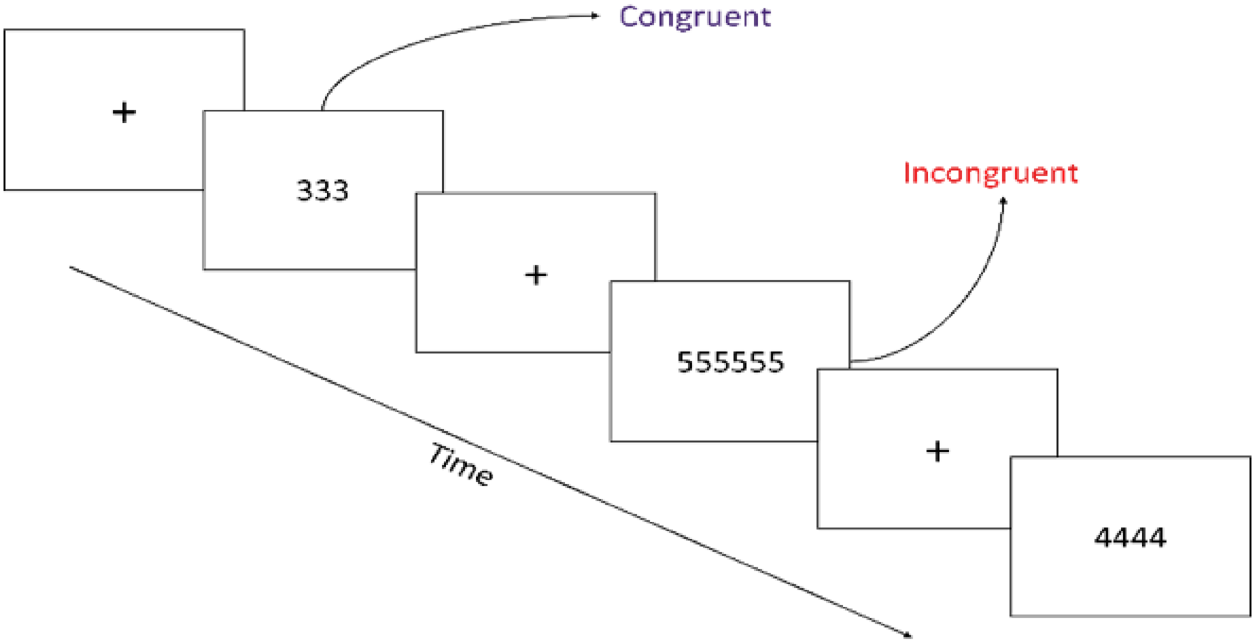


Fig. 1 Illustration of congruent and incongruent trial types presented during the Digit Stroop task

Self-Report Measures

Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003). This measure consists of 15 items designed to assess a core characteristic of dispositional or trait mindfulness, focusing on the attention and awareness aspects of mindfulness, rather than the attitudinal components of acceptance and non-judgment commonly emphasized in mindfulness-based interventions (Baer, 2003). All participants completed the validated scale using a 1–6 Likert scale (*almost always* to *almost never*). The scale has a single-factor structure, resulting in a single total score that measures mindfulness as a unidimensional construct. The final score is computed by calculating the mean responses of all 15 items. Higher scores indicate higher levels of dispositional mindfulness. Sample items include: “I do jobs or tasks automatically without being aware of what I am doing” and “I find myself doing things without paying attention” (both items are reverse scored).

Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006). This measure consists of 39 items designed to assess five factors that represent elements of mindfulness as it is currently conceptualized. It contains items from the Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003), the Freiburg Mindfulness Inventory (FMI; Walach et al., 2006), the Kentucky Inventory of Mindfulness Skills (KIMS; Baer et al., 2004), the Cognitive and Affective Mindfulness Scale (CAMS; Feldman et al., 2007) and the mindfulness Questionnaire (MQ; Chadwick et al., 2005). Baer et al. (2006) conducted an exploratory factor analysis to identify five common subscales or facets of mindfulness: *Observing*, *Describing*, *Acting with Awareness, Nonjudging of inner experience*, and *Nonreactivity to inner experience*. *Observing* includes noticing or attending to internal and external experiences (such as sensations, cognitions, and emotions); *Describing* involves the ability to articulate internal experience with words; *Acting with Awareness* refers to the attention directed to observing one’s activities in the present moment; *Nonjudging of Inner Experience* involves taking a non-evaluative stance towards thoughts and feelings; *Nonreactivity to Inner Experience* refers to disengaging from elaborative processing of thoughts or emotions that arise. Sample items include: “I notice the smells and aromas of things,” (*Observing*); “I am good at finding words to describe my feelings,” (*Describing*); “I find myself doing things without paying attention,” (*Act with awareness*; reverse-scored); “I think some of my emotions are bad or inappropriate and I should not feel them,” (*Nonjudging*; reverse-scored); and “I perceive my feelings and emotions without having to react to them,” (*Nonreactivity*). All items are rated on a 1–5 Likert scale (*Never or very* *rarely true* to *Very often or always true*). The ratings are added across each subscale to produce a total for each facet (ranging from 8 to 40) as well as a grand total for all five facets (ranging from 39 to 195). Higher scores indicate higher levels of facet or total dispositional mindfulness.

Experiment 2: Titrated Digit Stroop Task

Participants

Forty-two undergraduate students (35 females, mean age = 19.03, SD = 2.58) were recruited from McMaster University's Department of Psychology, Neuroscience & Behaviour participant pool. All participants had normal or corrected-to-normal vision and provided informed consent before they were compensated with research participant credit. All procedures complied with the Canadian Tri-Council Policy on Ethics and were approved by the McMaster Research Ethics Board.

Materials and Apparatus

Materials and apparatus were identical to Experiment 1.

Procedure

Procedure was identical to Experiment 1, except stimulus duration was manipulated to maintain accuracy level. On each trial, the stimulus duration randomly varied from 800 to 1200 ms and was titrated (+/- 20ms) 20 trials, to maintain an accuracy level between 70% and 80%. For example, if mean accuracy exceeded 80% on the previous 20 trials, the trial duration of the next 20 trials was decreased by 20 ms to increase difficulty. Similarly, if mean accuracy dropped below 70% on the previous 20 trials, the trial duration of the following 20 trials was increased by 20 ms. If participants were too slow at responding to a stimulus (response time exceeded stimulus duration), a warning appeared on the screen that read, "Too Slow!!!". In this way, task difficulty was maintained, while participants were required to adjust the speed of response accordingly. The task consisted of 1080 trials in total, randomly presented in 20 blocks of 54 trials with brief breaks were presented between each experimental block. The study was conducted in a single session that lasted an hour. Participants provided informed consent following verbal and written explanation of the experiment. All participants completed the Digit Stroop task before completing self-report measures to avoid any influence of mindfulness items on task performance. After completing the experiment, participants received research participation credit and a debriefing information sheet that summarized the details of the study.

Data Analysis

Response times were measured by calculating mean RT for congruent trials, incongruent trials, and total trials. Accuracy was measured by calculating proportion of correct trials out of correct and incorrect trials. Therefore, congruent accuracy was measured by calculating proportion of correct congruent trials; incongruent accuracy was measured by calculating proportion of correct incongruent trials; and total accuracy was measured by calculating proportion of all correct trials. The Stroop interference effect was calculated by subtracting the mean RT on congruent trials from the mean RT on incongruent trials. This difference was then used as a dependent variable in subsequent analyses. Post-error slowing (PES) was measured by calculating mean RT of correct trials following an error response. Congruent PES was measured by calculating mean RT on correct congruent trials following an error, incongruent PES was measured by calculating mean RT on correct incongruent trials following an error, and total PES was measured by calculating mean RT on all correct trials following an error. Finally, sequential congruency effects (SCE) were measured by calculating meant RT for four different dependent variables: mean RT for congruent trials preceded by congruent trials (cC), mean RT for congruent trials preceded by incongruent trials (iC), mean RT for incongruent trials preceded by congruent trials (cI) and mean RT for incongruent trials preceded by incongruent trials (iI).

Regression analyses were performed for all dependent variables of RT, accuracy, the Stroop interference effect, PES and SCE using MAAS and FFMQ scores as predictor variables. Single linear regressions were calculated to investigate whether MAAS and FFMQ total scores predicted RT, accuracy, the Stroop interference effect, PES, and SCE on both the non-titrated and titrated variations of the Digit Stroop (Experiment 1 and Experiment 2, respectively). We specifically hypothesized that overall dispositional mindfulness would predict better cognitive control performance in Experiment 2, where demands on cognitive control were increased and therefore correlations between mindfulness measures and task performance may be better detected. Multiple linear regressions were also calculated to identify which FFMQ facets (*Observing, Act with Awareness, Describing, Nonjudging* and *Nonreactivity*) predicted RT, accuracy, the Stroop interference effect, PES and SCE, and whether this relation was sensitive to varying cognitive control demands between experiments. Specifically, we hypothesized that *Observing* and *Act with Awareness* would predict RT, SCE and Stroop interference, whereas *Nonjudging* and *Nonreactivity* would predict differences in accuracy and PES and that these differences would be better detected in Experiment 2 than in Experiment 1.

Results

Table 1 and Table 2 present descriptive statistics for all dependent variables for Experiment 1 and Experiment 2, respectively. Table 3 and 4 present bivariate correlations for self-report mindfulness measures in Experiment 1 and Experiment 2, respectively.

Table 1. Descriptive Statistics for Experiment 1: Non-titrated Digit Stroop Task (n=44)

	Mean	Std Deviation	Std Error	Actual Range	Potential Range

MAAS Total	54.3864	11.50776	1.73486	32–80	15–90
MAAS Mean	3.477	0.76668	0.11558	2–5.33	1–6
FFMQ Total	118.7727	11.73190	1.76915	89–141	39–195
FFMQ Observe	23.7273	4.31527	0.65055	14–33	8–40
FFMQ Describe	24.7955	4.88748	0.73681	12–38	8–40
FFMQ Awareness	24.7045	5.35085	0.80667	12–39	8–40
FFMQ Nonjudgment	26.0227	6.46813	0.97511	12–40	8–40
FFMQ Nonreactivity	19.1364	3.50807	0.52886	12–27	7–35
Congruent RT	554.9925	40.84867	6.15817	464.15–630.26	—
Incongruent RT	616.7208	42.90055	6.4675	536.26–723.59	—
Total RT	583.9238	40.91094	6.16756	506.58–663.93	—
Post-Error Slowing Congruent RT	582.036	49.6184	7.48025	474.82–684.73	—
Post-Error Slowing Incongruent RT	648.8269	51.29326	7.73275	563.54–756.97	—
Post-Error Slowing Total RT	612.2205	46.57162	7.02094	511.26–702.50	—
Stroop Interference Effect (Incongruent–Congruent RT)	61.7283	16.88719	2.54584	26.76–114.43	—
Sequential Congruency Effect RT (cC)	547.5742	41.75268	6.29445	460.71–623.72	—
Sequential Congruency Effect RT (cI)	617.3781	44.69896	6.73862	517.56–714.07	—
Sequential Congruency Effect RT (iC)	560.2799	41.33267	6.23113	466.15–641.80	—
Sequential Congruency Effect RT (iI)	613.6236	43.34555	6.53459	548.73–733.33	—

Congruent Accuracy (proportion correct)	0.943	0.05896	0.00889	.61–1	—
Incongruent Accuracy (proportion correct)	0.8432	0.07637	0.01151	.56–.94	—
Total Accuracy (proportion correct)	0.8933	0.063	0.0095	.58–.97	—

Table 2. Descriptive Statistics for Experiment 2: Titrated Digit Stroop Task (n=42)

	Mean	Std Deviation	Std Error	Actual Range	Potential Range
MAAS Total	55.3810	13.97900	2.15701	31–79	15–90
MAAS Mean	3.6921	.93193	.14380	2.07–5.27	1–6
FFMQ Total	122.2143	22.34817	3.44840	64–182	39–195
FFMQ Observe	25.2381	5.73738	0.88530	13–36	8–40
FFMQ Describe	26.6190	5.82238	0.89841	14–39	8–40
FFMQ Awareness	24.2857	8.14289	1.25647	8–40	8–40
FFMQ Nonjudgment	25.4286	8.13347	1.25502	8–40	8–40
FFMQ Nonreactivity	20.6429	5.43171	0.83813	8–35	7–35
Congruent RT	588.5281	55.16112	8.51155	480.70–745.40	—
Incongruent RT	649.2555	58.71364	9.05971	517.43–799.62	—
Total RT	615.0732	56.44001	8.70888	499.50–769.09	—
Post-Error Slowing Congruent RT	602.2705	53.82753	8.30577	497.27–760.44	—
Post-Error Slowing Incongruent RT	662.1299	57.98123	8.9467	531.54–791.85	—
Post-Error Slowing Total RT	627.0609	54.49319	8.40848	512.45–774.69	—

Stroop Interference Effect (Incongruent–Congruent RT)	60.7273	18.04278	2.78406	31.98–117.21	—
Sequential Congruency Effect RT (cC)	584.8946	54.25326	8.27146	475.49–738.11	—
Sequential Congruency Effect RT (cI)	649.3267	60.43294	9.325	519.88–828.53	—
Sequential Congruency Effect RT (iC)	595.8803	54.3209	8.3819	484.72–743.29	—
Sequential Congruency Effect RT (iI)	648.3563	58.43633	9.01692	514.85–791.62	—
Congruent Accuracy (proportion correct)	0.8861	0.08827	0.01362	.48–.90	—
Incongruent Accuracy (proportion correct)	0.7257	0.09726	0.01501	.37–.86	—
Total Accuracy (proportion correct)	0.8083	0.08921	0.01376	.42–.91	—

Table 3. Bivariate Correlations for Self-Report Mindfulness Measures in Experiment 1: Non-titrated Digit Stroop Task (n=44)

Variable	1	2	3	4	5	6	7
1. MAAS	1						
2. FFMQ Total	-.322*	1					
3. FFMQ Observe	-.005	.434**	1				
4. FFMQ Describe	.023	.307*	.088	1			
5. FFMQ Awareness	-.386**	.690**	.074	-.037	1		
6. FFMQ Nonjudge	-.209	.539**	-.157	-.199	.484**	1	
7. FFMQ Nonreact	-.102	.230	.294	-.055	-.006	-.308*	1

** Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)

Table 4. Bivariate Correlations for Self-Report Mindfulness Measures in Experiment 2: Titrated Digit Stroop Task (n=42)

Variable	1	2	3	4	5	6	7
1. MAAS	1						
2. FFMQ Total	.747**	1					
3. FFMQ Observe	.203	.546**	1				
4. FFMQ Describe	.259	.615**	.342*	1			
5. FFMQ Awareness	.873**	.772**	.228	.244	1		
6. FFMQ Nonjudge	.696**	.784*	.148	.366*	.647*	1	
7. FFMQ Nonreact	.231	.528**	.335*	.185	.207	.207	1

** Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)

Experiment 1: Non-Titrated Digit Stroop Task

Linear and multiple regression analyses from Experiment 1 revealed that dispositional mindfulness did not significantly predict any measures of cognitive control performance when task demands were not manipulated. The MAAS and FFMQ did not significantly predict response times, accuracy, the Stroop interference effect, post-error slowing or sequential congruency effects in the non-titrated variation of the Digit Stroop task (all *p* values > .130).

Experiment 2: Titrated Digit Stroop Task

Single Linear Regressions

The MAAS significantly predicted the Stroop interference effect, $R^2 = .118$, $F(1,40) = 5.36$, $p = .026$, and also explained a significant proportion of the variance in the Stroop interference effect. Individuals with higher dispositional mindfulness scores on the MAAS showed a smaller Stroop interference effect, accounting for approximately 12% of the observed variance (see Figure 2). The MAAS did not significantly predict any other behavioural measure on the titrated Digit Stroop task (all *p* values > .619).

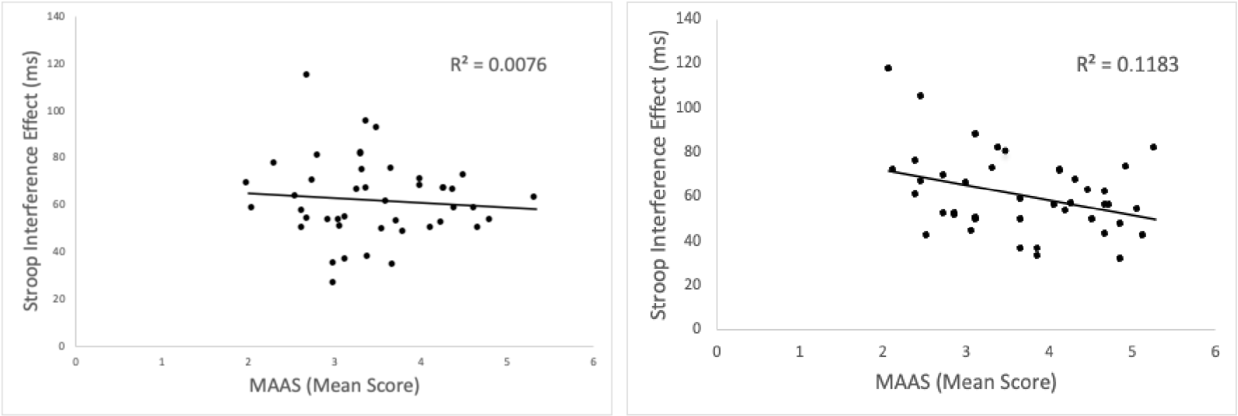

(a) Experiment 1: Non-Titrated Digit Stroop Task **(b) Experiment 2: Titrated Digit Stroop Task**

Fig. 2 MAAS as a predictor of the Stroop interference effect in (a) Experiment 1: Non-titrated Digit Stroop task and (b) Experiment 2: Titrated Digit Stroop task

Similarly, the total FFMQ score was also a significant predictor of the Stroop interference effect, $R^2 = .107$, $F(1,40) = 4.77$, $p = .035$. Individuals with higher FFMQ total scores also showed smaller Stroop interference effects, accounting for approximately 11% of the observed variance in the Stroop effect (see Figure 3).

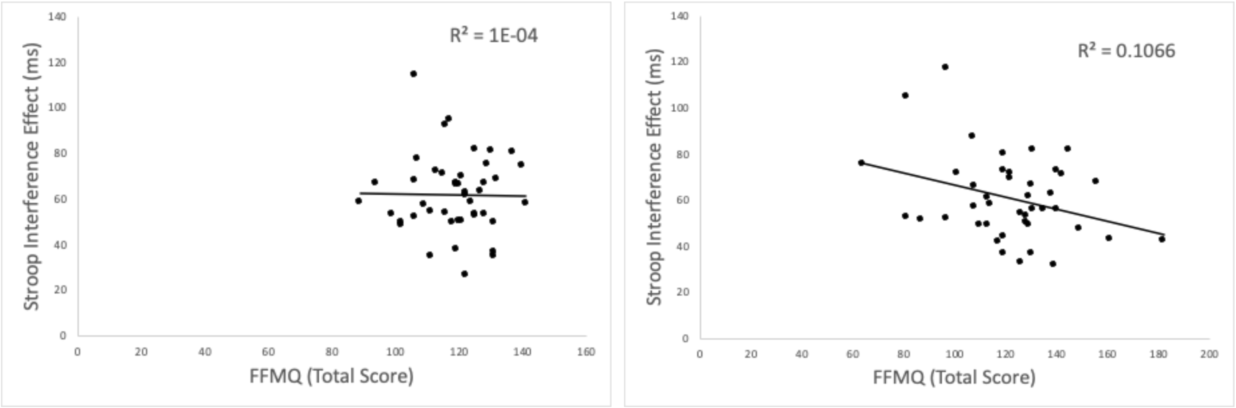
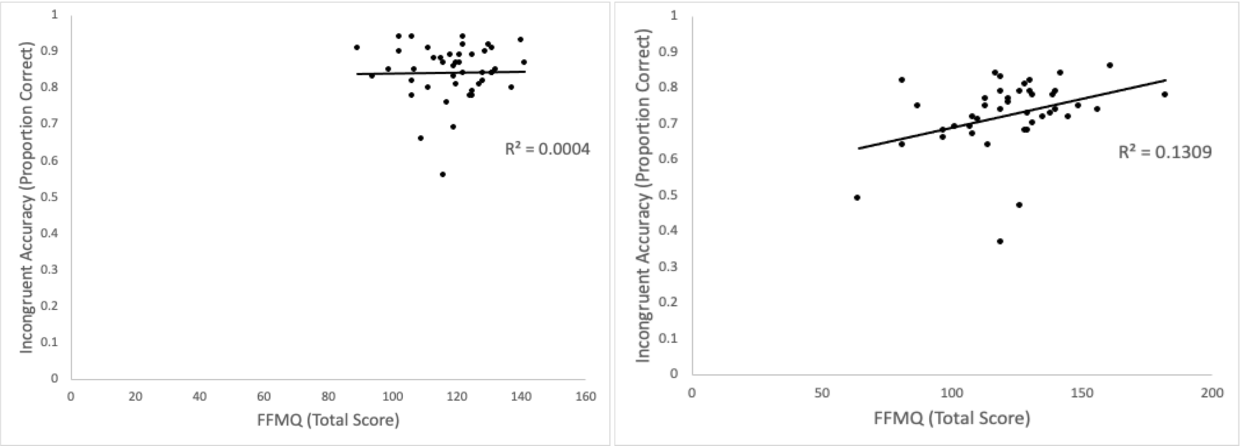

(a) Experiment 1: Non-Titrated Digit Stroop Task **(b) Experiment 2: Titrated Digit Stroop Task**

Fig. 3 FFMQ total score as a predictor of the Stroop interference effect in (A) Experiment 1: Non-titrated Digit Stroop task and (B) Experiment 2: Titrated Digit Stroop task

The total FFMQ score also significantly predicted incongruent accuracy, $R^2 = .133$, $F(1,40) = 6.12$, $p = .018$, explaining a significant proportion of the variance. Higher FFMQ total scores were associated with greater accuracy on incongruent trials, accounting for approximately 13% of the variance (see Figure 4).

The FFMQ did not significantly predict any other behavioural measure on the titrated Digit Stroop task (all p values > .085).



(a) Experiment 1: Non-Titrated Digit Stroop Task **(b) Experiment 2: Titrated Digit Stroop Task**

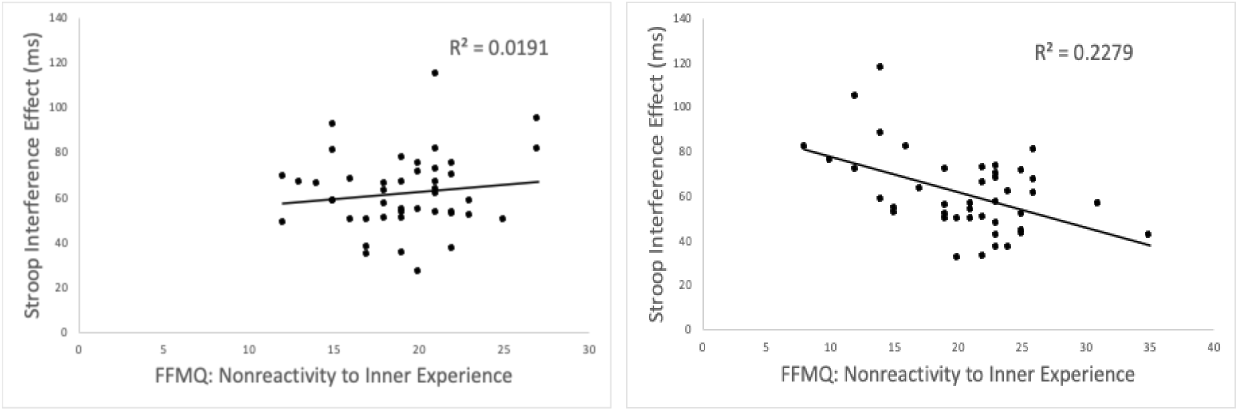
Fig. 4 FFMQ total score as a predictor of incongruent accuracy in (A) Experiment 1: Non-titrated Digit Stroop task and (B) Experiment 2: Titrated Digit Stroop task

Multiple Linear Regressions

Multiple regression analyses were calculated to identify which FFMQ facets were significant predictors of RT, accuracy, the Stroop interference effect, PES, and SCE. All facets were entered simultaneously as predictors of each multiple regression model.

FFMQ facets significantly predicted the regression model for the Stroop interference effect, $R^2 = .0.300$, $F(5,36) = 3.08$, $p = .020$, accounting for approximately 30% of the observed variance (see Figure 5). Specifically, only the *Nonreactivity to Inner Experience* facet significantly contributed to the model, B = -1.499, $t(36) = -3.00$, $p = .005$. Higher scores on the

Nonreactivity facet were associated with a smaller Stroop interference effect (see Figure 5). No other FFMQ facets significantly contributed to the model (all *p* values > .156).



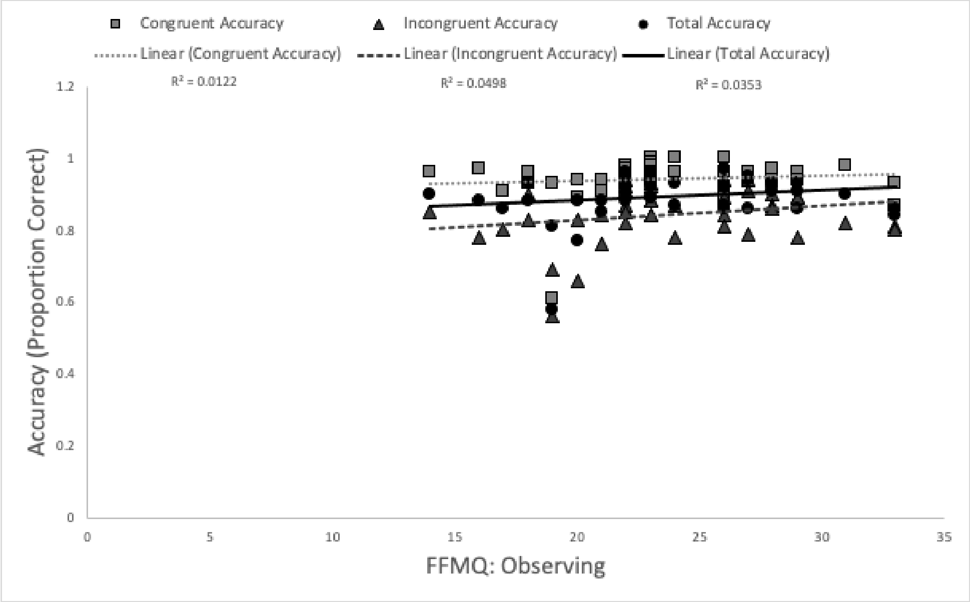
(a) Experiment 1: Non-Titrated Digit Stroop Task **(b) Experiment 2: Titrated Digit Stroop Task**

Fig. 5 FFMQ-Nonreactivity as a predictor of the Stroop interference effect in (A) Experiment 1: Non-titrated Digit Stroop task and (B) Experiment 2: Titrated Digit Stroop task

FFMQ facets also significantly predicted the regression model for congruent accuracy, *F*(5,36) = 2.68, *p* = .037, incongruent accuracy, *F*(5,36) = 4.55, *p* = .003, and total accuracy, *F*(5,36) = 3.68, *p* = 009, accounting for approximately 27%, 39% and 34% of the observed variance, respectively. Specifically, only the *Observing* facet significantly contributed to the model for congruent accuracy, B= .006, *t*(36) = 2.40, *p* = .022, incongruent accuracy, B = .007, *t*(36) = 2.80, *p* = .008, and total accuracy, B = .006, *t*(36) = 2.73, *p* = .010. Individuals who reported higher on the *Observing* facet showed greater accuracy on congruent trials, incongruent trials and total trials overall (see Figure 6). No other FFMQ facets significantly contributed to the model for congruent accuracy (all *p* values > .111), incongruent accuracy (all *p* values > .065), or total accuracy (all *p* values > .074).

The FFMQ facets did not significantly predict regression models for any other behavioural measure on the titrated Digit Stroop task (all *p* values > .440).

(a) Experiment 1: Non-Titrated Digit Stroop Task



(b) Experiment 2: Titrated Digit Stroop Task

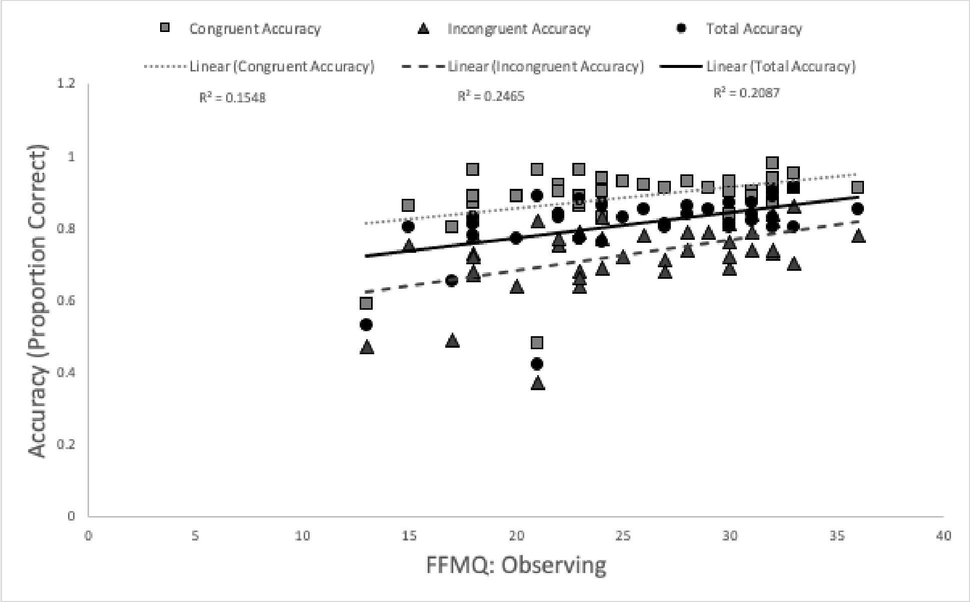


Fig. 6 FFMQ-Observing facet as a predictor of accuracy (proportion correct) in (A) Experiment 1: Non-titrated Digit Stroop task and (B) Experiment 2: Titrated Digit Stroop task

Discussion

We examined whether measures of dispositional mindfulness predict cognitive control performance on non-titrated and titrated variations of the Digit Stroop task. While numerous studies have examined the effects of mindfulness training on cognitive control, many such outcome studies did not account for pre-existing differences in dispositional mindfulness. Moreover, effects of mindfulness on cognitive control performance may not be observable unless task demands are sufficiently challenged, contributing to discrepancies in the literature. If individuals vary in their capacity to override dominant prepotent responses to task demands (e.g., overriding the reflexive tendency to name the *identity* of digits in an array when the task requires correctly identifying the *number* of digits in the array), we may not detect differential effects of varying cognitive control unless those capacities are pushed to their limits for each individual. By manipulating task demands in two variations of the Digit Stroop task, we were able to compare how measures of dispositional mindfulness predicted behavioural performance when cognitive control was systematically challenged for each individual. Although it remains unclear whether, in the present study, we tested limits of cognitive control capacity or if individuals were changing cognitive control strategies in this design, our manipulation nevertheless captures behavioural performance that corresponds with self-reported mindfulness.

Here, we hypothesized that our measures of dispositional mindfulness, the MAAS and FFMQ, would predict response times, accuracy, post-error slowing, the Stroop interference effect or sequential congruency effects in Experiment 2, where demands on cognitive control were increased and therefore associations between task performance and MAAS and/or FFMQ may be better detected. We also examined whether FFMQ facets (*Observing, Act with Awareness, Describing, Nonjudging* and *Nonreactivity*) predicted behavioural outcomes, and if they were sensitive to varying cognitive control demands between experiments. Taken together, our results indicate that facets of self-reported dispositional mindfulness may only be predictive of cognitive control performance when these processes are sufficiently challenged through task demands.

Consistent with our hypothesis, the MAAS and FFMQ were significant predictors of cognitive control performance when the task was manipulated to increase demands on cognitive control. We manipulated task difficulty by increasing or decreasing trial duration every 20 trials, identifying a threshold for each participant, thus allowing individual levels of cognitive control to be sufficiently challenged to detect deployment of attentional processes that overlap with self-reported dispositional mindfulness. By titrating the Digit Stroop task to maintain accuracy at 70–80%, we found that higher self-reported MAAS and FFMQ total scores predicted greater cognitive control as indexed by a smaller Stroop interference effect and higher FFMQ total scores predicted greater accuracy on incongruent trials. The results revealed further that whereas higher scores on the *Nonreactivity* facet predicted smaller Stroop interference, higher scores on the *Observing* facet predicted greater accuracy on congruent and incongruent trials.

This pattern of findings is in line with other evidence in the literature, where the *Observing* and *Nonreactivity* facets were significant predictors of performance on other cognitive tasks. For example, Anicha et al. (2012) conducted a study where they did three experiments using a visual working memory task, a temporal order judgment task and a colour-word Stroop task. The *Observing* facet predicted better performance on the visual working memory and temporal order judgment tasks while *Nonreactivity* and *Nonjudging* facets predicted smaller Stroop interference, which the authors interpreted as greater trial-to-trial cognitive flexibility. The authors suggest that whereas higher levels of *Observing* were associated with enhanced performance on the visual working memory and temporal order judgment tasks due to greater perceptual awareness, higher levels of *Nonreactivity* (and *Nonjudging*) were associated with a greater ability to upregulate or downregulate the cognitive control system in a way that is contextually adaptive. This interpretation is consistent with our results, where higher scores on *Observing* could reflect better perceptual awareness, leading to greater accuracy on congruent and incongruent trials, and higher scores on the *Nonreactivity* facet may reflect greater cognitive flexibility, leading to smaller Stroop interference. Nonetheless, self-reported mindfulness facets did not predict trial-to-trial cognitive flexibility, as measured by post-error slowing or the sequential congruency effect in the present study, rendering this interpretation only partially supported. Notably, self-reported levels of *Observing* and *Nonreactivity* did not correlate with one another in the series of experiments conducted by Anicha et al. (2012), which the authors suggest is further evidence of dissociable mindfulness skills that are not correlated with each other and are likely associated with different cognitive skills, a pattern replicated in previous studies (Cardaciotto et al., 2008; Baer et al., 2004). In contrast to Anicha et al. (2012), we found that *Observing* and *Nonreactivity* facets were significantly correlated in the sample from Experiment 2, but not Experiment 1. If mindfulness facets translate to dissociable cognitive skills, this introduces the possibility that our samples from Experiment 1 and Experiment 2 had dissimilar distributions of dispositional mindfulness facets that are associated with different cognitive skills. This difference in correlated mindfulness facets between experiments could partially explain why *Observing* and *Nonreactivity* were only predictors of performance in Experiment 2, reflecting higher levels of perceptual awareness *and* greater cognitive flexibility that together facilitate greater accuracy *and* smaller variation in response time, across all trial types. However, this is confounded by the key manipulation of titration in Experiment 2 and therefore cannot be confirmed in the present sent of data.

Other studies have also examined the relation between the FFMQ, attention and cognitive control but found diverging results. For example, Josefsson and Broberg (2011) investigated the relation between FFMQ facets and performance on the Sustained Attention to Response Task (SART; Robertson et al., 1997) and the Stroop task, finding that the total FFMQ score and the *Describe* facet predicted fewer errors on the SART, indicating that high scores on these two FFMQ scales were associated with fewer SART errors. Trends in the same direction were also found for the *Observe* and *Nonjudge* facets, but SART response time was not significantly related to the FFMQ at all. The *Describe* facet also significantly predicted Stroop interference; higher scores on *Describe* were related to low Stroop interference on the Stroop task, but no other significant relations were found between FFMQ and Stroop variables. Taken together, these findings suggest that high levels of self-reported mindfulness are related to better accuracy in sustained attention performance, but not response time. This lack of association between FFMQ and other Stroop variables is supported by previous studies that found no significant relation between mindfulness facets and Stroop performance (Lykins et al., 2012; Schmertz, 2009). This highlights the importance of replicating studies using tasks that sufficiently challenge cognitive control processes for each individual, where associations between facets of self-reported dispositional mindfulness on the FFMQ and task performance may be better detected.

Unlike the FFMQ, the MAAS measures mindfulness as a unidimensional construct with items designed to be free of specialized or metaphorical language, focusing on the attention and awareness aspects of mindfulness, but not the attitudinal components of acceptance and non-judgment that are emphasized across mindfulness-based clinical interventions (Baer, 2003). In the present study, the MAAS was only a significant predictor of smaller Stroop interference when participants' cognitive control processes were sufficiently challenged by maintaining accuracy at 70–80% in the titrated variation of the Digit Stroop task. It did not, however, significantly predict any other response time variables as we expected, including post-error slowing, or the sequential congruency effect. These results add to the inconsistent evidence surrounding the relation between single factor measures of dispositional mindfulness and behavioural performance on tasks of attention. For example, Schmertz (2009) examined the relation between various self-reported mindfulness measures and selective attention tasks, including the cued, single-trial Stroop task (Cohen et al., 1999; Seignourel et al., 2005), the Continuous Performance Test-II (CPT-II; Conners, 2000), and the Paced Auditory Serial Addition Test (PASAT; Gronwall & Sampson, 1977). In contrast to the present study, they found no significant association with self-reported mindfulness and cued Stroop interference scores, or number of errors made on incongruent trials. They also reported a null association between self-reported mindfulness and response time on the CPT-II, or percentage of correct responses on the PASAT, but the MAAS and the Cognitive and Affective Mindfulness Scale-Revised (CAMS-R; Feldman et al., 2007) were significantly correlated with CPT-II target omissions.

Whereas the MAAS, designed to measure mindfulness as a unidimensional construct, defines mindfulness as a "present-centered attention-awareness" (Brown & Ryan, 2003, p. 824), the CAMS-R is designed to assess four mindfulness components or skills: the regulation of attention, orientation to present experience, awareness of experience, and acceptance or non-judgment towards experience (Feldman et al., 2007). Like the MAAS, the CAMS-R is a 12-item single factor measure of mindfulness designed to assess the overall construct of mindfulness, and therefore may not be measuring mindfulness skills that are more predictive of behavioural indices in tasks of attention and cognitive control. Rather than measuring the complex construct of mindfulness, it is possible these unidimensional measures like MAAS are assessing attentional engagement or lapses. For example, Cheyne et al. (2006) found that the MAAS was a robust predictor not only of self-reported attention-related errors, but also behavioural measures of attentional lapses—SART errors and RTs. They also found a robust association of the MAAS and boredom proneness, pointing towards the impact of brief losses of attention in the maintenance of interest and engagement with our environment. Although the MAAS purports to measure mindfulness, Cheyne et al. (2006) suggest it is mislabeled and would be better characterized as a simple and direct measure of self-reported lapses in awareness. Studies of mindfulness also tend to focus on conflict trials themselves rather than on post-conflict performance. As Lippelt et al. (2014) suggests, mindfulness training may improve the ability to redirect attention after conflicting information or distraction is encountered and resolved. Evidence of mindfulness improving post-conflict resolution is supported by Grundy et al. (2018), who observed a strong negative relation between the MAAS and the size of post-conflict slowing (estimated by the size of bivalency effect; BE, Meier & Rey-Mermet, 2012; Woodward et al., 2003). This supports the interpretation that mindfulness may not just influence cognitive control processes while they are online during an individual trial, but that it also may modify cognitive control by allowing recovery more rapidly from conflict. Finally, these authors report that dispositional mindfulness had less influence on RT of conflict trials themselves, suggesting that the MAAS is more heavily associated with post-conflict recovery processes than with conflict resolution. Critically, this work highlights the importance of using a variety of experimental paradigms to isolate the nuanced influences of mindfulness attention regulation on cognitive control processes.

One major limitation with any dispositional mindfulness study concerns whether we are measuring the same "mindfulness" phenomenon as other studies in the literature, particularly when dispositional mindfulness can change with training. For example, whereas Zeidan et al. (2011) found within-subject increases on the Freiburg Mindfulness Inventory (FMI; Walach et al., 2006) after 4 days of mindfulness training, Hölzel et al. (2011) also showed significant increases in *Act with Awareness*, *Observing* and *Non-Judging* FFMQ facets after an MBSR intervention. Several within- and between-subject studies also document self-reported MAAS increases after MBSR interventions (Jensen et al, 2012; Kilpatrick et al., 2011), which begs the question: how trait-like or dispositional is mindfulness if it is sensitive to changes? It is also important to note that our study uses two different samples from two different projects and timelines. As Grossman (2011) has argued, trainees are likely to endorse mindfulness scale items differently at the end of training than at baseline. Therefore, although Experiment 2 data were collected at baseline, before any training occurred, the enrollment in a training study alone could have influenced the way participants self-reported dispositional mindfulness in Experiment 2 compared to Experiment 1, which was not part of a longitudinal design. We need to also consider that dispositional mindfulness, or the mindful capacity one embodies without meditation experience, may be different from state mindfulness, when one engages in mindfulness practice. Self-report measures rely on one's perception of their own mindful abilities/attitudes, and perceived mindfulness may not reflect attentional processes engaged during actual mindfulness. Finally, central to the purpose of this study, when we manipulated accuracy in Experiment 2, we also manipulated the speed-accuracy trade-off (Wickelgren, 1977). Therefore, caution is warranted in the interpretation of these data, particularly given a reliance on behavioural measures involving response times. Although the lack of relation between self-reported mindfulness and response time variables (i.e., congruent RT, incongruent RT, total RT, PES, and SCE) resembles other evidence in the literature, we cannot interpret response time data in the same way for the titrated Digit Stroop task in Experiment 2. Nonetheless, the lack of relation between dispositional mindfulness and these response time variables in both experiments suggests that the influence of accuracy manipulations on the speed-accuracy trade-off in the Digit Stroop task may be less relevant for studies involving self-reported mindfulness.

It remains possible that training or deploying attention more broadly generalizes to a variety of functional domains (Posner & Rothbart, 2007). This implies that with or without formal mindfulness training, exercising attention may also be exercising mindful capacities, if they are overlapping domain-general skills. Therefore, to detect mindful capacities (or self-reported mindfulness), we need to sufficiently challenge overlapping attention and cognitive processes. Our study demonstrates that experimental manipulations of task difficulty are simple yet effective ways to challenge and detect cognitive control processes, particularly in paradigms where performance is typically high. Future cognitive control studies should consider titrating stimulus duration in a way that identifies a specific threshold of behavioural performance, for each individual. Another simple consideration involves using digits instead of words to eliminate influences from word associations that could exist with colour-word Stroop paradigms, such as grapheme-colour synaesthesia (Jancke et al., 2009). Instead of colour words, we used an array of numbers which are devoid of word-reading effects and ubiquitous in daily life. Introducing six key responses (1–6) also increased the likelihood of errors, consequently challenging task difficulty. This experimental paradigm is particularly beneficial for electrophysiological studies of performance monitoring that require more error trials for analysis of error related ERPs. More studies should take self-report measures of mindfulness into account, particularly before and after mindfulness inductions or interventions to account for variation in attentional engagement in one's current state or situation. Whether or not these questionnaires are tapping into mindfulness phenomena, they may be reliable predictors in accounting for variability in behavioural performance in tasks of attention and cognitive control. The *Observing* and *Nonreactivity* facets, in particular, may be tapping into two processes that are qualitatively different in individuals' ability to deploy attention: *Observing*, which involves attending to internal or external stimuli in the current situation, and *Nonreactivity*, which requires disengaging from elaborative processing of the internal or external stimuli (sensations, cognitions, emotions). Indeed, these two mindfulness facets may reflect core attentional skills that are deployed in mindfulness and cognitive control: focusing attention and awareness on relevant information, while ignoring irrelevant information and responding accordingly to fluctuations in present moment demands.

Literature that investigates how self-report measures predict individual differences in attention and cognitive control remains lacking. Here, we show that facets of self-reported dispositional mindfulness, specifically *Observing* and *Nonreactivity*, may reflect or overlap with deployment of domain general attentional processes that account for variability in cognitive control performance. This may not be detected, however, unless cognitive control processes are sufficiently challenged in a task designed to vary demands. By manipulating task demands in this way, we present a novel manipulation of a cognitive control task and show that variation in dispositional mindfulness can account for variability in behavioural performance. Future studies should take dispositional mindfulness into account before evaluating state and trait-dependent outcomes of mindfulness induction or intervention. Finally, future studies should also experimentally challenge task demands to detect and measure the degree of overlap between mindfulness capacities and cognitive control processes.

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Chapter 3—The Impact of Mindfulness Training on Electrophysiological Indices of Cognitive Control

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Abstract

Few studies examine the effects of mindfulness training on neurophysiological indices of enhanced attention and cognitive control. Of these few, large discrepancies in experimental design related to operationalization of the mindfulness construct and nature of the control group(s) used have led to conflicting results. Here, we address this discrepancy by introducing a novel active control condition (guided visual imagery meditation) to isolate the specific effects of mindful attention regulation on cognitive control in a carefully controlled longitudinal training study. We examine changes to behavioural task performance and stimulus and response-locked event-related potentials (ERPs) extracted from continuous electroencephalogram (EEG) recorded while participants completed the Digit Stroop task before and after two weeks of daily 20-minute mindfulness or active control training. Although mindful and control groups did not differ behaviourally after training, electrophysiological differences emerged at the N2, P3a, P3b, and ERN components, revealing increased efficiency in conflict detection and monitoring of stimuli with varying degrees of cognitive interference (attenuated N2 amplitude), delayed automatic capture of attention by incongruent stimulus features (delayed P3a latency of incongruent stimuli), faster conscious evaluation of all stimulus features (earlier P3b latencies), and delayed automatic detection of errors (delayed ERN latencies) after mindfulness training. These findings are discussed in terms of the cognitive control processes that vary as a function of mindfulness attention regulation training.

Introduction

In recent decades, the widespread scientific interest in mindfulness has generated research that has established various adaptive neurobiological, psychological and behavioural outcomes, expanding our empirical understanding of the construct. Although modern scientific inquiry of mindfulness is relatively recent, the deliberate exercise of mindful attention regulation has been practiced for 2,500 years as a way to observe and gain insight into ongoing events and experiences. Broadly conceptualized as present-centered and non-judgmental awareness, mindfulness involves maintaining meta-cognitive awareness of the current experience while sustaining attention to task-relevant features and disengaging from elaborative processing of irrelevant information (Kabat-Zinn, J., 1990; Bishop et al., 2004). Because mindfulness is fundamentally a construct concerning attention, an emerging body of literature has explored the convergence (and divergence) between mindfulness and related attentional constructs, most notably executive function and cognitive control. Here, we refer to cognitive control as the set of executive cognitive processes that select and successfully monitor information relevant to current goals while ignoring or inhibiting irrelevant information, thereby facilitating information processing and behaviour to vary adaptively moment to moment depending on these chosen goals (Morton et al., 2011; Cohen et al., 2000; Botvinick et al., 2001; Posner et al., 2004). By focusing attention on present goals and re-directing attention from distractions, mindfulness training enhances moment-to-moment awareness of fluctuations in cognitive demands. As a result, meditators can develop greater control over a set of cognitive processes that promote useful behavioural adaptations. Several studies have documented the influence of mindfulness on executive functions (Jha et al. 2007; Moore & Malinowski, 2009; Semple, 2010; Teper and Inzlicht, 2013), however, the precise mechanisms underlying the impact of mindfulness on different aspects of executive functioning are still unclear. Based on Miyake et al.'s (2000) unity and diversity view, which defines executive functioning in three subdomains (e.g., inhibition of irrelevant information, updating working memory and shifting attention), Gallant (2016) proposed that mindfulness training enhances inhibitory control. The most consistent findings belong to behavioural studies that examined the effect of mindfulness training on conflict resolution and inhibitory control using stimuli that present competing streams of information and response selection, such as the Stroop task (Stroop, 1935; e.g., Allen et al., 2012; Moore & Malinowski, 2009; Teper & Inzlicht, 2013). However, some behavioural studies examining conflict resolution and inhibitory control showed little to no effect of mindfulness training on cognitive control performance (*Stroop*: Anderson et al, 2007; Moore et al., 2012; *Flanker*: Larson et al., 2013), leading to discrepant findings and cautious interpretations of cognitive mechanisms underlying mindfulness.

Discrepancies in Experimental Design

More recently, electrophysiological studies have attempted to provide further insight into neurocognitive mechanisms underlying mindfulness by using the high temporal resolution of electroencephalography (EEG) and event-related potentials (ERPs) to examine the precise neural underpinnings of mindfulness and cognitive control. Still, only few studies examine the effects of mindfulness training on ERPs associated with various cognitive control mechanisms. Of these few, discrepancies in experimental design have led to conflicting results. In particular, mindfulness is typically operationalized three different ways: as a trait-like outcome of long-term formal practice in experienced meditators, as a state evoked by brief induction in novice or naive meditators, or as an inherent disposition that varies across individuals measured using psychometric tools. Therefore, electrophysiological studies of mindfulness and cognitive control vary greatly depending on how the mindfulness construct itself is operationalized. While some cross-sectional studies have examined the impact of long-term mindfulness practice in experienced meditators (Teper & Inzlicht, 2013; Atchley et al., 2016), other cross-sectional designs have examined the impact of brief mindfulness induction in naive meditators (Larson et al., 2013; Saunders et al, 2016; Bing-Canar et al., 2016; Norris et al., 2018), characterizing two extremes of mindfulness expertise and their impact on cognitive control. Other electrophysiological studies have operationalized and measured mindfulness as an inherent disposition using psychometric assessments, but their interpretations are limited by test validity, reliability and the distribution of responses used to categorize participants into groups of high mindfulness and low mindfulness based on a median split (Quaglia et al., 2016; Eichel et al., 2017). This highlights the value of carefully controlled longitudinal studies that examine electrophysiological correlates of cognitive control before and after a mindfulness intervention. At present however, this limited literature lacks the inclusion of appropriate control conditions to contrast and isolate the precise cognitive control mechanisms that are distinct to mindfulness training. For example, some studies compare a mindfulness training group with waitlist controls who are not engaging in any training program between testing sessions (Moore et al., 2012; Schoenberg et al., 2014) while others compare mindfulness training with active control groups, who are engaging in activities varying from psychoeducation training to brain training exercises (Smart & Segalowitz, 2017; Malinowski et al., 2017). To date, no mindfulness studies document both stimulus-locked and response-locked ERPs within a longitudinal design using a population of healthy younger adults.

Electrophysiological Indices of Mindfulness and Cognitive Control

In the cognitive electrophysiology literature, event related brain potentials (ERPs) are components extracted from the ongoing, naturally occurring brain activity recording using electroencephalogram (EEG). ERPs are precisely time-locked to either stimulus onset, or participant response. The most reliable ERP markers of the neurophysiological processes underlying attention regulation, cognitive control and performance monitoring include the N2, P3a and P3b waveforms which are time-locked to the onset of stimulus (i.e., stimulus-locked), as well as the ERN and Pe waveforms, which are time-locked to the onset of response (i.e., response-locked).

The N2 is a negative deflection that occurs 200 to 400 ms post-stimulus with an anterior scalp distribution and is considered a signature of conflict monitoring and inhibition (Bruin et al., 2001; Donkers & Van Boxtel, 2004; Niewenhuis et al., 2003; Folstein & Van Petten, 2008). Mindfulness has been mainly associated with an increased N2 amplitude, suggesting an increase in control processes related to conflict detection and monitoring of competing stimulus features as well as premotor inhibitory suppression of incorrect responses (Atchley et al., 2016; Malinowski et al., 2017; Norris et al., 2018; Quaglia et al., 2016), although there are some inconsistencies that need further investigation. For example, Schoenberg et al. (2014) found no modulation of the N2 in a population of individuals with Attention Deficit Hyperactivity Disorder (ADHD) post-mindfulness intervention, suggesting that mindfulness training may not always influence processes related to conflict monitoring or inhibition, especially among populations with clinically significant deficits in attention regulation. Additionally, Moore et al. (2012) observed an increased negative deflection that peaked between 160 and 240 ms over occipito-parietal regions of the left and right hemispheres during the colour-word Stroop task, which the authors described as increased N2 amplitudes after mindfulness training. However, this component reported by Moore et al. (2012) may better fit the profile of the N1 component—a negative deflection observed 130 to 190 ms post-stimulus immediately after the first positive ERP component known as the P1 (observed 80 to 130 post-stimulus) (Ahumada-Mendez et al., 2022). Both the P1 and N1 components are related to sensory processing in visual cortices and are modulated by focus of attention with scalp distributions located at occipital electrode sites in the hemisphere contralateral to the stimulus location (Debruille et al., 2019; Ahumada-Mendez et al., 2022). Although previous research has shown early ERP components such as P1 and N1 are sensitive to tasks that require spatial and feature-based selective attention (Hillyard & Münte, 1984; Mangun, 1995; Zhang & Luck, 2009), David et al. (2011) also observed an increase in the parietal-occipital N1 during a Stroop matching task using a latency window of 160–200 ms post-stimulus, providing evidence of early selection processing during a Stroop-like task. Therefore, it is conceivable that the increased N2 component reported by Moore et al. (2012) is in fact an N1 component, which suggests that mindfulness may modulate sensory processing by focus of attention, observed in the P1 and N1 components.

The P3 or P300, one of the most studied ERP components, has a broad positive amplitude related to stimulus task relevance and a latency that reflects stimulus evaluation time (Folstein & Van Petten, 2008; Johnson & Donchin, 1980). The P3 can be divided into two subcomponents: P3a and P3b (Polich, 2007). The P3a is a medial-frontal positivity that peaks approximately 300 to 400 ms post-stimulus, has a focal anterior scalp distribution and is thought to reflect unconscious, involuntary or automatic allocation of attention, or attentional capture, to significant or unexpected events (Bush et al., 2000; Muller-Gass et al., 2007; Salisbury et al., 1992; Escera et al., 2001; Folstein & Van Petten, 2008). Using participants with 20 years of Vipassana meditation experience, Cahn and Polich (2009) compared performance on an auditory oddball task after 30 minutes of mindfulness (Vipassana) meditation or 30 minutes of random thinking (mind-wandering). They found a lower P3a amplitude during the meditative state relative to the mind-wandering state and this reduction in amplitude was correlated positively with mindfulness meditation practice frequency, suggesting that mindfulness is associated with reduced stimulus-driven attentional capture. While the P3a is considered a stimulus-driven electrophysiological index that originates from frontal attention mechanisms during task processing, the P3b is thought to reflect temporal-parietal activity associated with conscious attention and subsequent memory processing (Polich, 2007). The P3b is observed 300–500 ms after stimulus onset and is widely considered a signature of conscious access to or conscious processing of a stimulus (Dehaene & Changeux, 2011). In tasks that require attention to task-relevant stimuli, such as an auditory oddball task, mindfulness has been associated with greater P3b amplitude (Atchley et al., 2016; Delgado-Pastor et al., 2013; Smart et al., 2016) indicating increased allocation of attention to relevant stimuli. However, mindfulness has also been associated with a reduced P3b amplitude during tasks that require inhibition of task-irrelevant information (i.e., distractor tones during an auditory oddball task, Atchley et al., 2016; irrelevant stimuli during an attentional-blink task, Slagter et al., 2007; irrelevant stimuli during Go/Nogo task, Howells et al., 2012; or competing alternatives during a Stroop task, Moore et al., 2012). Finally, some studies show no effect of mindfulness on the P3b during similar tasks, such as the Attention Network Task (ANT; Fan et al., 2002; Norris et al., 2018) or the Stroop task (Malinowski et al., 2017), leading to inconclusive interpretations of P3b modulation (and their respective control mechanisms) after mindfulness training.

Two of the most reliable neural markers associated with performance monitoring are the error-related negativity (ERN) and the error positivity (Pe). The ERN is a negative deflection with a medial-frontal scalp distribution that peaks within 100 ms after error commission and is considered an index of error monitoring and evaluative control (Falkenstein et al., 2000; Gehring et al., 2012; Endrass & Ullsperger, 2014). Although there are divergent theories on the functional significance of the ERN, most agree it is modulated by attention in response to errors (Friedman, 2012; Gehring et al., 2012; van Noordt et al., 2016; van Noordt et al., 2015; van Noordt & Segalowitz, 2012). The error positivity (Pe) is a positive deflection that peaks around 100 to 200 ms after error commission, is usually larger on trials with greater conscious awareness of an error and is thought to reflect motivational significance of errors (Steinhauser & Yeung, 2012; Logan et al., 2015). Whether or not mindfulness increases attentiveness to errors (increased ERN) or decreases affective salience associated with errors (decreased Pe) is mixed in the literature. Some studies showed an increased ERN associated with mindfulness (Teper & Inzlicht, 2013; Smart & Segalowitz, 2017; Eichel et al., 2017; Saunders et al., 2016) while other studies showed a decrease or no change in the ERN (Larson et al., 2013; Schoenberg et al., 2014; Bing-Canar et al., 2016). Similarly, the direction of Pe modulation is unpredictable, with some studies showing an increased Pe amplitude (Schoenberg et al., 2014), some studies showing a decreased P3 amplitude (Larson et al., 2013), and other studies showing no change in Pe associated with mindfulness (Teper & Inzlicht, 2013; Smart & Segalowitz, 2017; Saunders et al., 2016; Bing-Canar et al., 2016).

Overview and Hypotheses

Taken together, the majority of evidence shows that mindfulness is associated with modulations of ERPs associated with conflict monitoring (N2), automatic allocation of attention (P3a), conscious stimulus evaluation (P3b), error monitoring (ERN and Pe) and may also influence ERPs related to early sensory processing sensitive to selective attention (P1 and N1).

By using the high temporal resolution ERPs associated with early sensory processing, conflict monitoring, allocation of attention, conscious stimulus evaluation and error monitoring, we can establish an information processing timeline of neural activity in mindfulness meditators from the time of stimulus presentation to response completions. Here, we used a novel control condition (guided visual imagery meditation) in a carefully controlled longitudinal training study to isolate the unique effects of mindfulness training on both stimulus-locked and response-locked electrophysiological indices of cognitive control during the Digit Stroop task. The Digit Stroop task is a variation of the classic colour-word Stroop task (Stroop, 1935; MacLeod, 1991) where participants are presented with an array of identical digits and are instructed to correctly respond to the number of digits while ignoring the identity of the digits. EEG was used to record ongoing neural activity while participants completed the Digit Stroop task before and after two weeks of daily 20-minute guided mindfulness meditation practice or guided visual imagery practice (active control group). Consistent with formal mindfulness training procedures, the mindfulness meditation training condition instructed individuals to focus their attention internally on the sensations of their breath; observe distracting thoughts, feelings or sensations without judgment or elaboration; and re-direct attention back to their breath. Our active control condition also presented guided training, however, attention was oriented externally to the narration of a nature walk, where elaboration of distracting thoughts, feelings or sensations was embraced with no explicit re-direction of attention to the narration or visualization. Critically, both conditions presented a type of guided meditation, so that the specific training offered by mindfulness meditation could be effectively isolated. Compared to the passive attention regulation in guided visual imagery meditation, the specific practice of sustaining focus, disengaging from distractions and re-directing attention practiced in mindfulness meditation was hypothesized to alter neural activity in a way that will be reflected in unique changes to ERP markers of attention and cognitive control. Specifically, we hypothesized that the mindful practice of sustaining focus on relevant task features (number of digits) would facilitate early sensory processing sensitive to selective attention, resulting in increased P1 and N1 amplitudes overall. We also hypothesized that mindfulness training would facilitate greater inhibition and disengagement from task irrelevant features (i.e., identity of digits), reflected by an increased N2 amplitude, while decreasing automatic capture of stimulus-driven attention, reflected by a decreased P3a amplitude, particularly on incongruent trials where there are competing streams of information processing between stimulus features. We also predicted that the deliberate disengagement of attention from task irrelevant features and redirection of attention to relevant task features would lead to more efficient evaluation and conscious processing of stimuli after mindfulness training, reflected by decreased P3b amplitudes and faster P3b latencies (faster processing time) compared to the active control group. Finally, we also hypothesized that the deliberate disengagement of elaborative processing and redirection of attention to present task goals would facilitate "nonjudgmental acceptance" when errors are committed, leading to attenuated salience and conscious awareness of errors after mindfulness training. Thus, we predicted decreased ERN and Pe amplitudes after mindfulness training and increased ERN and Pe amplitudes after active control group, particularly for the more salient congruent errors. Although the impact of mindfulness training on behavioural indices of executive function are inconsistent in the existing literature, we predicted behavioural outcomes that correspond with the hypothesized electrophysiological changes associated with enhanced cognitive control, including faster response times, greater accuracy, reduced Stroop interference, and decreased post-error slowing (PES).

Methods

Participants

Forty-six undergraduate and graduate students were recruited from online advertisements at McMaster University's Department of Psychology, Neuroscience & Behaviour. Participants were randomly assigned to either a mindfulness group or an active control group. Two participants from the mindfulness group and 5 participants from the active control group dropped out for personal or health reasons unrelated to the study itself. Therefore, final study enrollment included 21 participants (13 female) in the mindfulness group and 18 (14 female) in the active control group. However, two EEG data files from the mindfulness group as well as two EEG data files and one behavioural data file from the control group were corrupted during data management and transfer, so the final analysis included 38 participants (21 mindfulness, 17 control) for behavioural analysis and 35 participants (19 mindfulness, 16 control) for ERP analysis. Exclusion criteria included previous meditation experience, uncorrected visual impairment, current or previous diagnosis of psychiatric disorders, neurological disorders, head injury with loss of consciousness, or current use of psychopharmacological treatments. Thus, all participants were neurologically and psychiatrically healthy individuals unpracticed in meditation. All procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Ethics Research Board.

Procedure overview

This experiment was part of a larger longitudinal training study that consisted of a baseline testing session, two weeks of daily mindfulness or active control training, followed by a final testing session. The order of study procedures was identical between the mindfulness and active control groups. During the baseline testing session, all participants provided written informed consent before completing self-report measures and performing the experimental tasks while EEG was recorded. Participants were then randomly assigned to two weeks of daily mindfulness or active control training (details below). Immediately after the last day of training, all participants completed their final testing session while EEG was recorded. To ensure a mindful or active control state, participants completed their respective training exercise immediately before they completed the final experimental tasks while EEG was recorded. Participants then completed post-training self-report measures before they were debriefed. Each experimental session lasted ~3 h in duration, as several other tests were carried out that are not reported in this paper.

Self-Report Measures

Demographic Information

All participants completed a basic demographic questionnaire that surveyed age, level of education and any previous meditation experience.

Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003)

This measure consists of 15 items designed to assess a core characteristic of dispositional or trait mindfulness. All participants completed the validated scale using a 1–6 Likert scale (*almost always* to *almost never*). The scale has a single-factor structure, resulting in a single total score. The final score is computed by calculating the mean responses of all 15 items. Higher scores indicate higher levels of trait mindfulness. Sample items include: “I do jobs or tasks automatically without being aware of what I am doing” and “I find myself doing things without paying attention” (both reverse scored).

Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006)

This measure consists of 39 items designed to assess five factors that represent elements of mindfulness as it is currently conceptualized. It contains items from the Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003), the Freiburg Mindfulness Inventory (FMI; Walach et al., 2006), the Kentucky Inventory of Mindfulness Skills (KIMS; Baer et al., 2004), the Cognitive and Affective Mindfulness Scale (CAMS; Feldman et al., 2007) and the mindfulness Questionnaire (MQ; Chadwick et al., 2005). Baer et al. (2006) conducted an exploratory factor analysis to identify five common subscales or facets of mindfulness: *Observing*, *Describing*, *Acting with Awareness, Nonjudging of inner experience*, and *Nonreactivity to inner experience*. *Observing* includes noticing or attending to internal and external experiences (such as sensations, cognitions, and emotions); *Describing* involves the ability to articulate internal experience with words; *Acting with Awareness* refers to the attention directed to observing one's activities in the present moment; *Nonjudging of Inner Experience* involves taking a non-evaluative stance towards thoughts and feelings; *Nonreactivity to Inner Experience* refers to disengaging from elaborative processing of thoughts or emotions that arise. Sample items include: "I notice the smells and aromas of things," (*Observing*); "I am good at finding words to describe my feelings," (*Describing*); "I find myself doing things without paying attention," (*Act with awareness*; reverse-scored); "I think some of my emotions are bad or inappropriate and I should not feel them," (*Nonjudging*; reverse-scored); and "I perceive my feelings and emotions without having to react to them," (*Nonreactivity*). All items are rated on a 1–5 Likert scale (*Never or very rarely true* to *Very often or always true*). The ratings are added across each subscale to produce a total for each facet (ranging from 8 to 40) as well as a grand total for all five facets (ranging from 39 to 195). Higher scores indicate higher levels of facet or total trait mindfulness.

Freiburg Mindfulness Inventory (FMI; Walach et al., 2006)

The FMI is a 14-item inventory designed to measure the experience of mindfulness. Participants rate statements such as "I am open to the experience of the present moment" on a four-point scale from 1 (rarely) to 4 (always). Scores range from 14 to 56 with higher scores indicating a higher degree of mindfulness. The FMI was used as a manipulation check to evaluate whether participants were engaged in a mindful state and whether this changed after training (Zeidan et al., 2010).

Mindfulness and Active Control Training Sessions

Both the mindfulness and active control training sessions consisted of four 20-minute in person group sessions led by an experienced meditation instructor. Each group training session consisted of 2 to 10 people and was distributed evenly across the two-week program. Participants also received a 20-minute guided training video, led by the same instructor, to maintain consistent individual practice on each of the remaining days. To maintain consistency over the two weeks, the meditation instructor used the same mindfulness or active control script for both group and video training sessions. In the mindfulness training sessions, participants were instructed to focus their attention internally on the sensations of their breath; observing distracting thoughts, feelings or sensations without judgment or elaboration; and re-directing attention back to their breath. This is consistent with formal mindfulness training procedures. The active control condition also presents guided training, however, attention is oriented externally to the narration of a nature walk, where elaboration of distracting thoughts, feelings or sensations is experienced with no explicit re-direction of attention to the narration or visualization. Critically, both conditions present a type of guided meditation, so that the neurocognitive mechanisms underlying specific training offered by mindfulness meditation can be effectively isolated.

Materials and Apparatus

All stimuli were presented on Pentium class computer with Presentations® experimental control software (Neuro Behavioural Systems; version 14.3) on a 17-inch CRT monitor with a refresh rate of 85 Hz. The stimuli appeared in black, sans-serif numerals in the center of a grey background. Visual angle of the stimuli ranged from 5˚ to 6˚ horizontally between left and right edges of the outermost numbers and from 3˚ to 4˚ vertically between upper and lower edges of the outermost numbers. A chinrest was used to maintain a consistent viewing distance of approximately 80 cm between participants.

The Digit Stroop task

The Digit Stroop task is a variation of the classic Stroop task, used to measure cognitive control and executive attention (Stroop, 1935). The task stimuli were strings of 1 to 6 digits presented in the center of a grey screen. All digits in the array had the same identity (1, 2, 3, 4, 5, or 6) and the number of digits presented varied randomly. The digits were mapped to computer keys along the bottom edge of the keyboard: "z x c" were used for left hand responses and represented digits 1, 2, 3, respectively, while ", . /" were used for right hand responses and represented digits 4, 5, 6, respectively. Participants were asked to respond as quickly and as accurately as possible by identifying the number of digits in the string, while ignoring the identity of the digits themselves. For example, the correct response to the stimulus, "5 5 5 5" is 4 (there are 4 digits) and is executed by pressing the "," key. The stimulus set consisted of equal congruent and incongruent trials. On congruent trials, the string length was equivalent to the identity of the digit presented (e.g., the correct answer to "6 6 6 6 6 6" is '6'). On incongruent trials, the string length did not match the digit identity (e.g., the correct answer to “3 3” is “2”). In between trials, a fixation cross (+) was displayed at the center of the screen for an inter-trial interval (ITI) that varied randomly from 400 to 800 milliseconds. On each trial, the stimulus duration randomly varied from 800 to 1200 milliseconds. The task consisted of 540 trials in total, presented in 10 blocks of 54 trials. To reduce blinking and general movement that might interfere with task-relevant ERPs, a message appeared after every 10 trials indicating that participants could take a “blink break”. Brief breaks were also provided between each experimental block. Participants resumed the experiment by pressing one of the response keys to start the next trial.

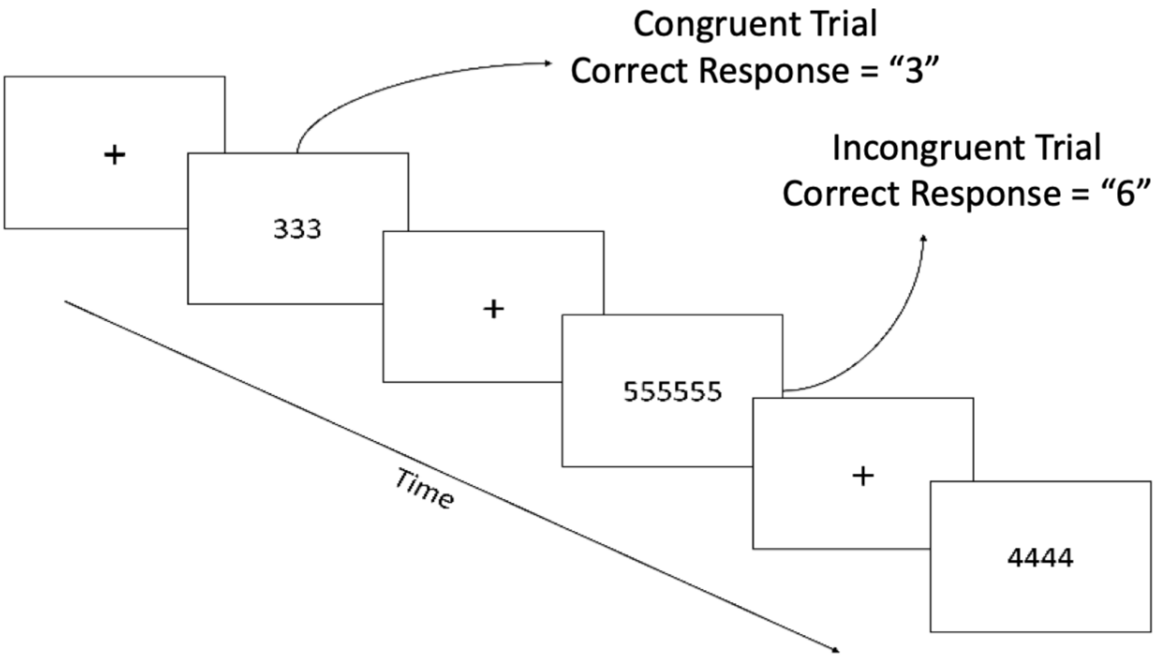

Figure 1. Illustration of congruent and incongruent trial types presented during the Digit Stroop Task. Inter-trial-interval (ITI) was randomized between 400 and 800 ms. Stimulus duration was randomized between 800 and 1200 ms. The task consisted of 540 trials (50% congruent, 50% incongruent) randomly presented in 10 experimental blocks consisting of 54 trials.

Electrophysiological Recording

Continuous EEG activity was recorded from 128 Ag/AgCl scalp electrodes with a BioSemi ActiveTwo amplifier system (BioSemi, Amsterdam, Netherlands). Four electrooculogram (EOG) electrodes were placed at the outer canthi and just below each eye to monitor horizontal and vertical eye movements for removal of trials with eye artifact. Two additional electrodes, a common mode sense (CMS) active electrode and a driven right leg (DRL) passive electrode were also used. These electrodes replace the "ground" electrodes used in conventional systems (www.biosemi.com/faq/cms&drl.htm). The continuous signal was acquired with an open passband from DC to 150 Hz and digitized at 512 Hz. The signal was bandpass filtered offline at 0.1 to 30 Hz using a Hamming windowed FIR filter and re-referenced to a common average reference. Bad channels were interpolated using the three nearest channels if the standard deviation of the channel exceeded 200mV before computing the average reference. Offline signal processing and averaging were done using EEGLAB version 13.5.4b (Delorme & Makeig, 2004) and ERPLAB version 5.0 (Lopez-Calderon & Luck, 2014). Infomax ICA algorithm (Bell and Sejnowski, 1995) was computed and artifactual independent components or epochs containing artifacts (e.g., muscle or eye movements) were removed manually after visual inspection. EEG was segmented, binned and epoched from -300ms prestimulus to 900ms post-stimulus. A pre-stimulus baseline correction from -300ms to -100ms was applied to avoid correcting anticipatory potentials like the ERN.

Behavioural and ERP Data Analysis

Response times were measured by calculating mean RT for congruent trials, incongruent trials, and total trials. Accuracy was measured by calculating proportion of correct trials out of correct, incorrect and miss trials. Therefore, congruent accuracy was measured by calculating proportion of correct congruent trials; incongruent accuracy was measured by calculating proportion of correct incongruent trials; and total accuracy was measured by calculating proportion of all correct trials. Post-error slowing (PES) was measured by calculating mean RT of correct trials following an error response. Congruent PES was measured by calculating mean RT on correct congruent trials following an error, incongruent PES was measured by calculating mean RT on correct incongruent trials following an error, and total PES was measured by calculating mean RT on all correct trials following an error. Finally, the Stroop interference effect was calculated by subtracting the mean RT on congruent trials from the mean RT on incongruent trials. This difference score was then used as a dependent variable in subsequent analyses.

Visual inspection of the ERP waveform across electrode sites and stimulus conditions revealed that the time windows for extraction of the mean amplitude, peak amplitude and peak latency for each ERP component. The P1 and N1 were best captured by small clusters of left parietal-occiptal electrodes (PO7 and PO5) and right parietal-occipital electrodes (PO8 and PO6). Therefore, mean amplitude, peak amplitude and peak latency were extracted and averaged for left (PO7 and PO5) and right (PO8 and PO6) electrode clusters from a time window of 60 to 120 ms for the P1 component and a time window of 120 to 220 ms for the N1 component. The fronto-central N2 and P3a were best captured at electrode FCz by a time window of 250 to 350 ms and 325 to 425 ms, respectively. The P3b was on average ~250-450 ms after stimulus onset and was maximally represented at electrode site Pz. Therefore, mean amplitude was calculated using a time window of 250 to 450 ms, while peak amplitude and peak latency was extracted from a 200 to 500 ms time window to ensure peaks were captured during extraction. These time windows are consistent with previous literature examining the P3b during Stroop task performance (Moore et al., 2012; Malinowski et al., 2017). The ERN and Pe were best captured at the FCz electrode by a time window of –50 to 100 ms and 75 to 300 ms, respectively.

Results

Self-Report Measures

Independent samples t-tests were conducted to assess differences between baseline variables for the two intervention groups. At baseline, participants in the mindfulness and control group did not differ on any of the included variables (all *p* values > .199.) However, there was a significant difference on Levene's Test for Equality of Variances for the baseline FFMQ-Observe subscale (*F* = 9.99, *p* = .003), which suggests unequal variances among groups. A Welch's t-test (for unequal variances) confirmed that the baseline FFMQ-Observe scores were not significantly different from one another [*t*(22.795) = .88, *p* = .390].

Repeated measures ANOVAs with *Group x Time* as factors were conducted for the MAAS, FFMQ, and the FMI to assess group differences across time of training (i.e., *Group x Time* interactions). There was no significant main effect of *Group*, *Tim*e or significant *Group x Time* interactions for the MAAS, FFMQ Total, FFMQ Describe or FFMQ Acting with Awareness measures (all *p* values > .083). There was a main effect of *Time* for FFMQ-Observe [*F*(1,36) = 14.20, p < .001], FFMQ-Nonjudge [*F*(1,36) = 6.72, *p* = .014], and FFMQ-Nonreact [*F*(1,36) = 7.28, *p* = .011]. Both groups showed significant increase on the FFMQ-Observe and FFMQ-Nonreact facets, as well as a significant decrease on the FFMQ-Nonjudge facet after training. There was also a significant main effect of *Time* [*F*(1,36 = 12.74, *p* = .001] and a significant *Group x Time* interaction [*F*(1,36) = 6.59, *p* = .015] for the FMI scale. Post-hoc pairwise comparisons using the Bonferroni correction showed that FMI scores significantly increased for the mindfulness group after training (from 31.143 before to 36.190 after, mean difference of 5.048, p < .001) but did not significantly change for the control group (from 32.706 before to 33.529 after, mean difference of .824, *p* = .505). They also showed that the mindfulness and control group were not significantly different from each other before (*p* = .426) or after training (*p* = .202). Therefore, both the main effect of *Time* and the *Group x Time* interaction were driven by the significant increase of FMI scores after mindfulness training.

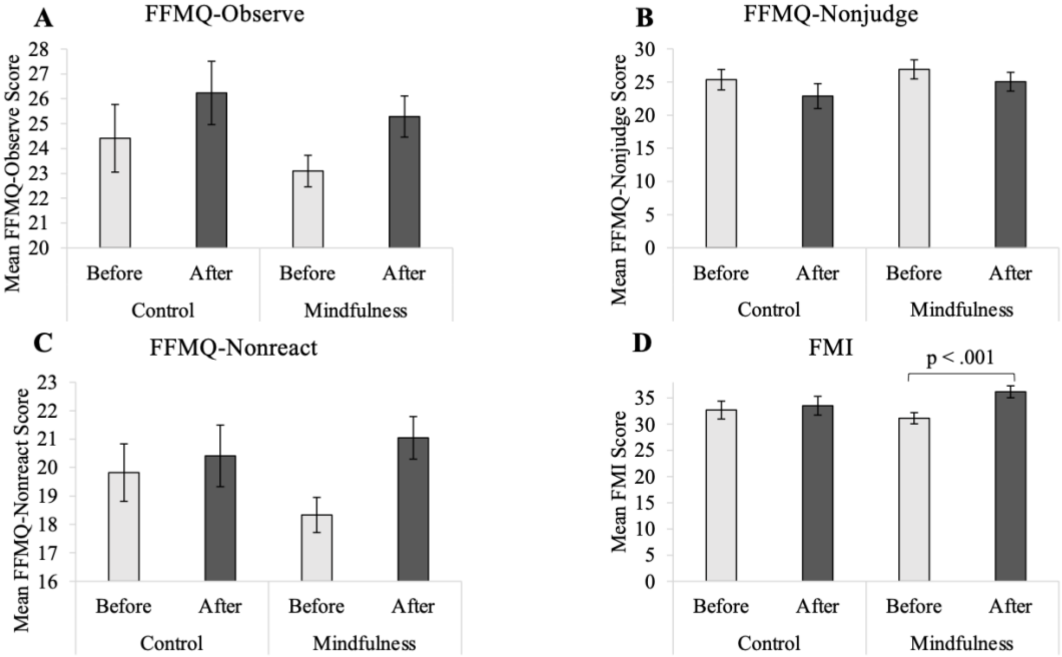

Figure 2. Mean scores for each group across time depicted for (**A**) the Observe subscale of the Five Facet Mindfulness Questionnaire (FFMQ), (**B**) the Nonjudge subscale of the FFMQ, (**C**) the Nonreact subscale of the FFMQ and (**D**) the Freiburg Mindfulness Inventory (FMI). Overall, scores increased over time in both groups for the (**A**) FFMQ-Observe (p < .001) and the (**C**) FFMQ-Nonreact (p = .011), while scores decreased over time in both groups for (**B**) FFMQ-Nonjudge (p = .014). Post-hoc pairwise comparisons for a significant Time x Group interaction (p = .015) revealed that only the mindfulness group showed a significant increase on (**D**) FMI scores after training (p < .001). Error bars represent standard errors.

Behavioural Results

A series of 2 x 2 x 2 mixed repeated measures ANOVAs with *Group x Time x Congruency* as factors were conducted for response times (RTs), accuracy and Post Error Slowing (PES). 2 x 2 mixed repeated measures ANOVAs with *Group x Time* as factors were conducted for total RT, total accuracy, total PES and the Stroop interference effect. Post-hoc pairwise comparisons using the Bonferroni correction were conducted to interpret significant interactions. Independent samples t tests were also conducted to assess baseline differences between groups, which showed no significant difference at baseline between the mindfulness group and the control group.

Response Time (RT)

Group x Time x Congruency mixed repeated measures ANOVA revealed a significant main effect of *Time* [$F(1,36) = 37.12$, $p < .001$], a significant main effect of *Congruency* [$F(1,36) = 710.85$, $p < .001$], a significant *Congruency x Time* interaction [$F(1,36) = 43.70$, $p < .001$] and a significant *Congruency x Group* interaction [$F(1,36) = 5.29$, $p = .027$]. Overall, as expected, response times for congruent trials are faster than response times for incongruent trials (congruent = 523.83 ms, incongruent = 572. 66 ms, p < .001). Post-hoc pairwise comparisons using the Bonferroni correction for the *Congruency x Time* interaction showed that RT significantly decreased (got faster) after training for both congruent trials (from 556.36 ms to 539.20 ms, p < .001) and incongruent trials (from 619.77 ms to 589.12 ms, p < .001), but this mean difference was greater for incongruent trials (–30.65 ms) than congruent trials (–17.17 ms). The difference in RT between congruent and incongruent trials (Stroop interference effect) was also significantly different before training (p < .001) and after training (p < .001) but this mean difference was greater before training (–63.41 ms) than after training (–49.92 ms). Post-hoc pairwise comparisons were also conducted to interpret the significant *Congruency x Group* interaction, which showed that the difference between congruent and incongruent trials overall was significant for both the control group (congruent = 551.09 ms, incongruent = 612.65 ms, p < .001) and the mindfulness group (congruent = 544.467 ms, incongruent = 596.25 ms, p < .001), but this mean difference (incongruent – congruent) was greater for the control group (61.55 ms) than the mindfulness group (51.78 ms). The ANOVA showed no other significant effects (all *p* values = .402).

Group x Time repeated measures ANOVA for Total RT had a significant main effect of *Time* [*F*(1, 36) = 35.46, *p* < .001], which revealed that overall, Total RT decreased after training (from 586.06 ms to 562.82 ms). No other no other significant effects were observed (all *p* values > .428).

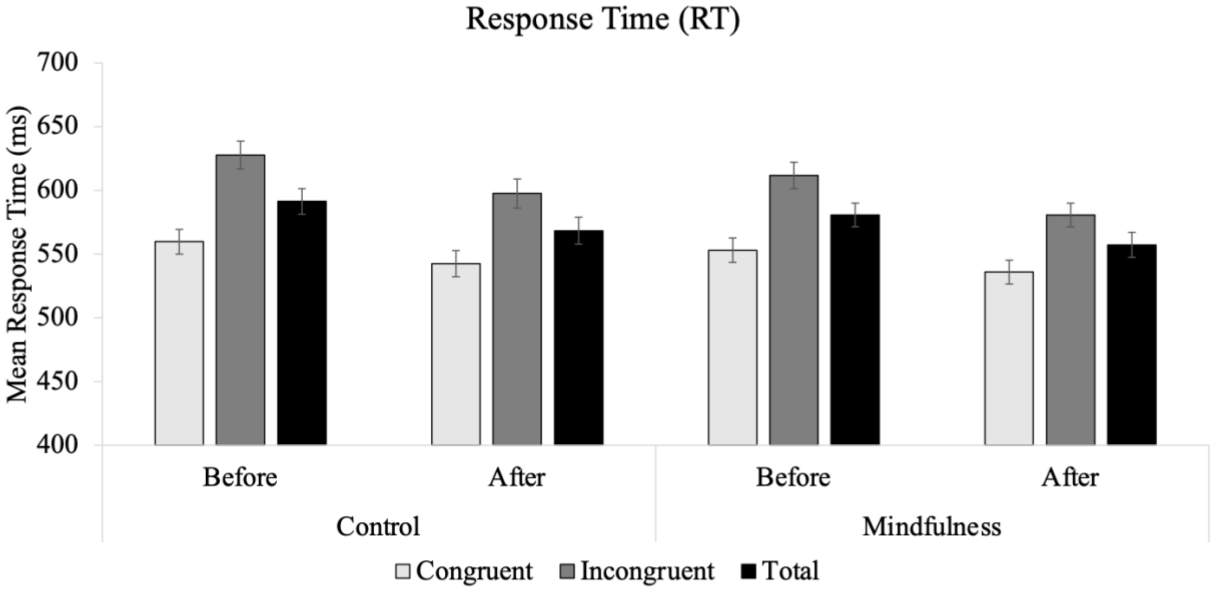

Figure 3. Mean response time (RT) in milliseconds (ms) for congruent trials, incongruent trials and total trials (collapsed across congruency) organized by group, before and after training. Overall, congruent RTs were significantly faster than incongruent RTs (ME of Congruency, p < .001). After training, the change in RTs for incongruent trials was significantly greater than the change in RTs for congruent trials (Congruency x Time, p < .001). RTs for congruent and incongruent trials were also significantly faster for both groups after training (ME of Time, p < .001), however the difference in RTs for congruent and incongruent trials was greater for the control group overall (Congruency x Group, p = .027). Error bars represent standard errors. ME = Main Effect.

Accuracy

Group x Time x Congruency repeated measures ANOVA showed a significant main effect of *Time* [*F*(1,36) = 4.64, *p* = .038] and a significant main effect of *Congruency* [*F*(1,36) =

159.92, $p < .001$]. As expected, accuracy on congruent trials (94.7%) was greater than accuracy on incongruent trials (85.3%). *Group x Time* repeated measures ANOVA for Total Accuracy showed a significant main effect of *Time* [$F(1,36) = 4.67$, $p < .037$]. Overall, total accuracy increased over time (from 88.9% to 91.2%). No other significant effects were observed for accuracy (all p values > .060).

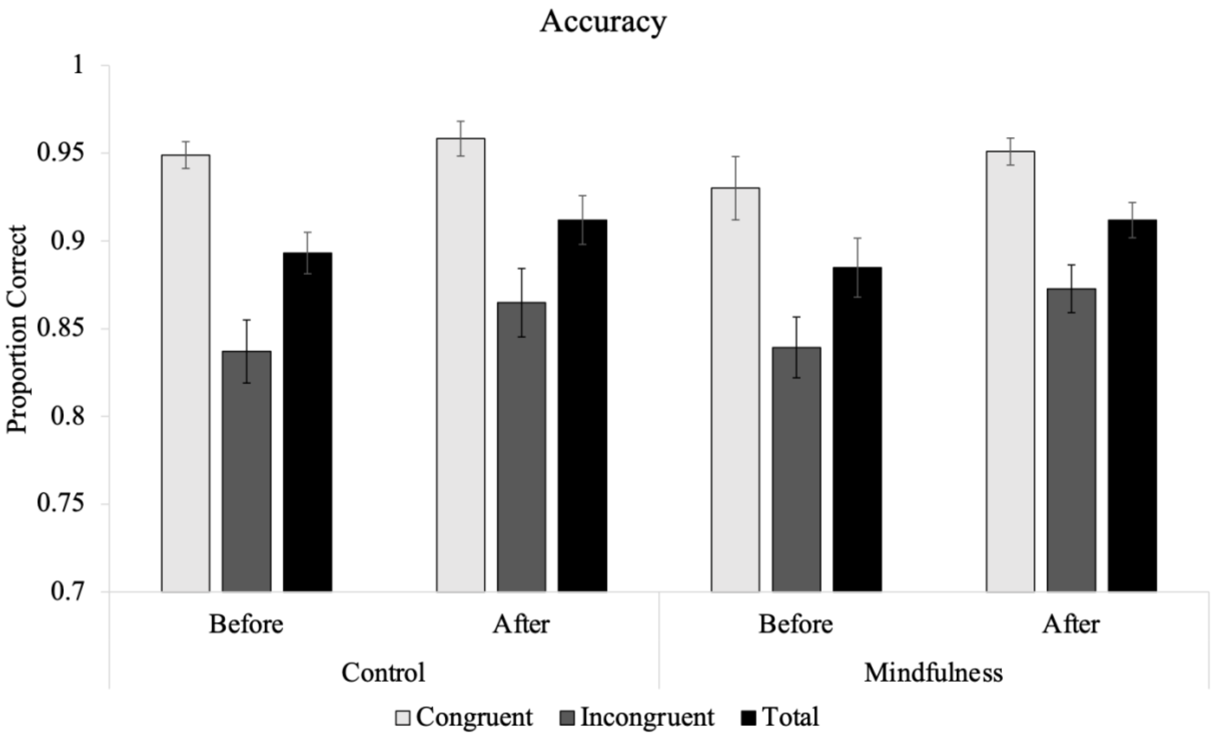

Figure 4. Accuracy depicted by proportion correct of congruent trials, incongruent trials and total trials organized by group, before and after training. Overall, accuracy was greater on congruent trials than incongruent trials (p < .001) and increased after training for both groups (p = .038). Error bars represent standard errors.

Post-Error Slowing (PES)

Group x Time x Congruency repeated measures ANOVA showed a significant main effect of *Time* [$F(1,36) = 14.10$, $p < .001$] and a significant main effect of *Congruency* [$F(1,36) = 138.97$, $p < .001$]. After training, PES decreased from 612.00 ms to 586.50 ms (response time after an error did not slow as much as it did at baseline). As expected, PES on congruent trials

(568.32 ms) was also smaller than on incongruent trials (630.19 ms). *Group x Time* repeated measures ANOVA for Total PES response times showed a significant main effect of *Time* [$F(1,36) = 13.47$, $p < .001$]. After training, Total post-error slowing decreased (from 608.94 ms to 584.96 ms) regardless of group. No other significant effects were observed for post-error slowing (all p values > .069).

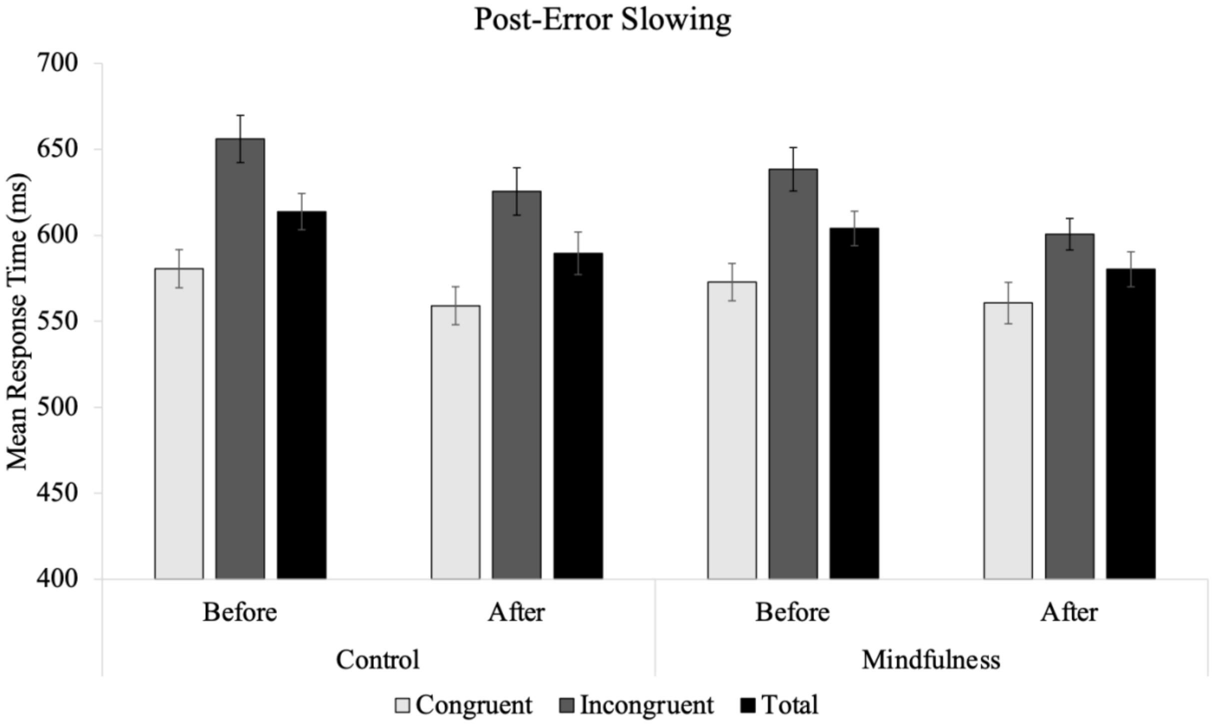

Figure 5. Mean response times (RT) in milliseconds (ms) for post-error slowing (PES) of congruent trials, incongruent trials and total trials organized by group, before and after training. Overall, PES was smaller on congruent trials than incongruent trials (p < .001), and decreased after training for both groups (p < .001). Error bars represent standard errors.

Stroop Interference Effect

Group x Time repeated measures ANOVA for the Stroop effect showed a significant main effect of *Time* [$F(1,36) = 43.70$, $p < .001$] and a significant main effect of *Group* [$F(1,36) = 5.29$, $p = .027$]. After training, the Stroop interference effect was smaller (decreased from 63.41 ms to 49.92 ms). However, both groups were significantly different from one another overall: the

Stroop effect in the control group was significantly larger (61.55 ms) than in the mindfulness group (51.78 ms) regardless of testing time point.

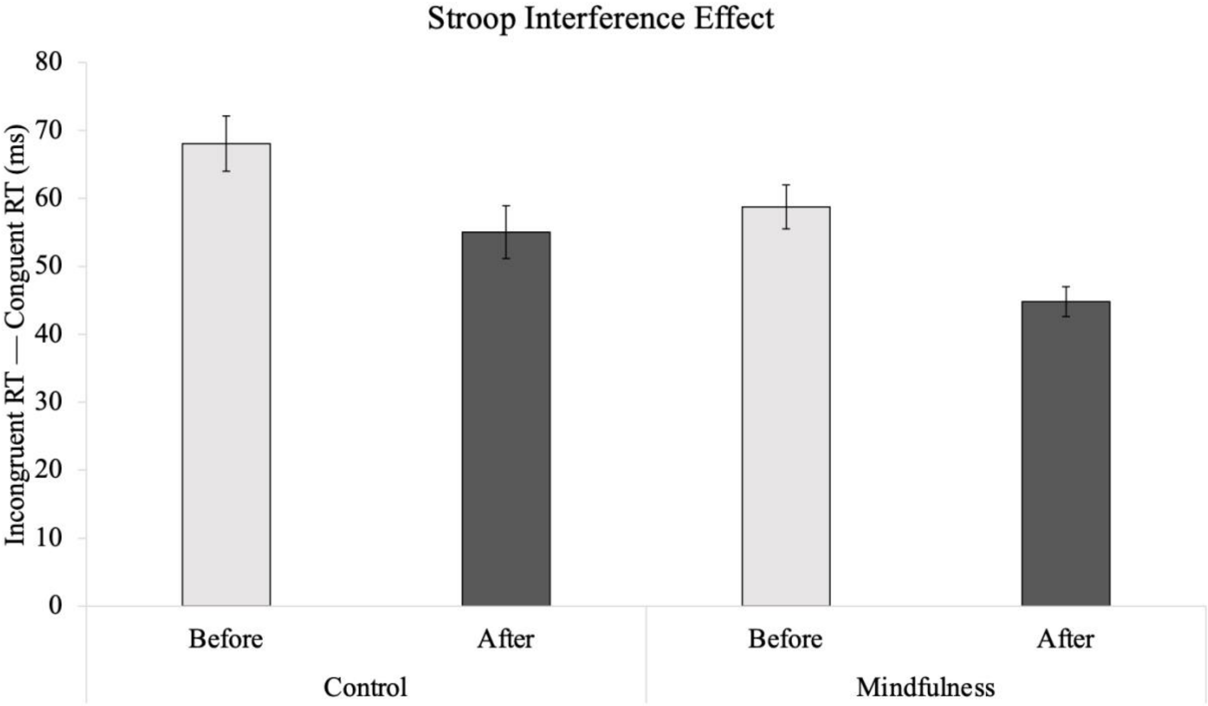

Figure 6. Mean response times (RT) in milliseconds (ms) for the Stroop interference effect (the difference between RT for congruent and incongruent trials) organized by group, before and after training. Overall, the Stroop interference effect was larger for the control group than the mindfulness group (p = .027) and decreases after training for both groups (p < .001). Error bars represent standard errors.

ERP Results

2 x 2 x 2 mixed repeated measures ANOVAs with *Group x Time x Congruency* as factors were conducted to examine the role of each variable in the mean amplitudes, peak amplitudes and peak latencies of the P3b waveform at Pz electrode site, the N2, P3a, ERN, and Pe waveforms at FCz at the electrode site and maxima of the bilateral P1 and N1, which were best captured by small clusters of left parietal-occipital electrodes (PO7 and PO5) and right parietal-occiptal electrodes (PO8 and PO6).

P1 at PO7/PO5 and PO8/PO6 (60 to 120 ms)

The left and right P1 waveforms at the PO7/PO5 cluster and the PO8/PO6 cluster are depicted in Figure 7. *Group x Time x Congruency* ANOVAs revealed a significant main effect of *Group* for the left P1 peak latency [*F*(1,33) = 5.13, *p* = .030]. Overall, the left P1 peak latency occurred earlier for the mindfulness group (93.37 ms) than the control group (101.23 ms) indicating earlier sensory processing sensitive to selective attention in the mindfulness group. No other significant effects were observed for the P1 waveform at the left or the right cluster (all *p* values > .112 and .071, respectively).

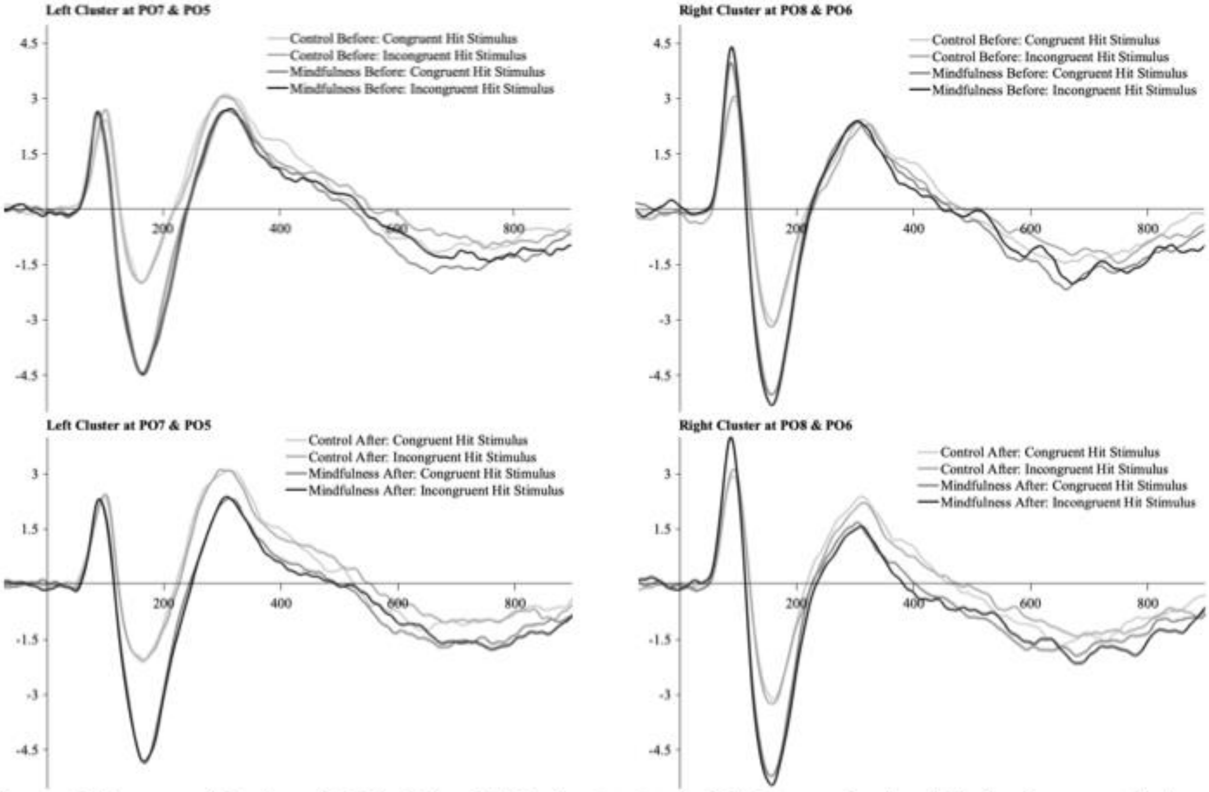

Figure 7. Top panel: Left and Right P1 and N1 stimulus-locked ERPs are depicted for both groups before training. Bottom panel: Left and Right P1 and N1 stimulus-locked ERPs are depicted for both groups after training. Left clusters: PO7 & PO5. Right clusters: PO8 & PO6. P1 latency window: 60–120ms, N1 latency window: 120–220ms.

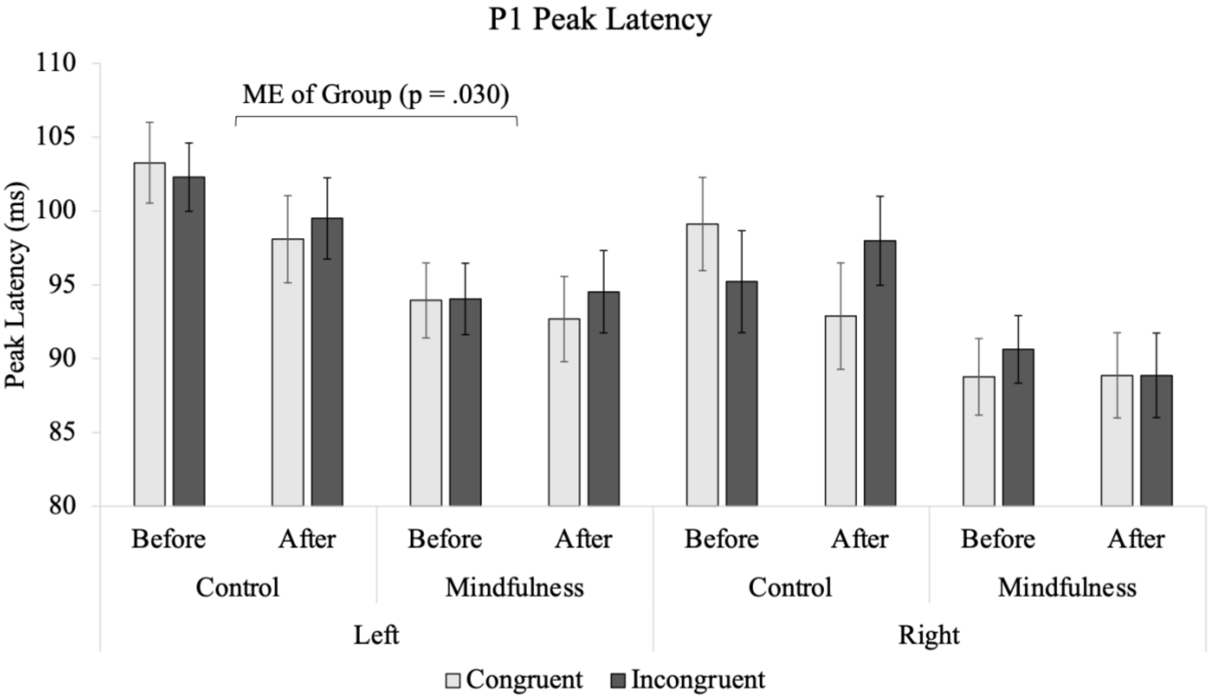

Figure 8. P1 peak latencies in milliseconds (ms) collapsed across congruency for control and mindfulness groups organized by hemisphere (left electrode clusters: PO7, PO5; right electrode clusters: PO8, PO6). Overall, the mindfulness group had a significantly earlier P1 peak latency compared to the control group, but only in the left hemisphere (p = .030). Error bars represent standard errors.

N1 at PO7/PO5 and PO8/PO6 (120 to 220 ms)

The left and right N1 waveforms at the PO7/PO5 cluster and the PO8/PO6 cluster are depicted in Figure 7. *Group x Time x Congruency* ANOVAs revealed a significant main effect of *Group* for the left N1 mean amplitude [$F(1,33) = 9.69$, $p = .004$] and peak amplitude [$F(1,33) = 4.29$, $p = .046$] and a significant main effect of *Congruency* for the right N1 mean amplitude [$F(1,33) = 9.65$, $p = .004$] and peak amplitude [$F(1,33) = 5.25$, $p = .028$]. Overall, the left N1 mean and peak amplitudes were larger for the mindfulness group (mean amplitude: –3.07 μV, peak amplitude: –5.02 μV) than the control group (mean amplitude: –1.13 μV, peak amplitude: –3.16 μV), suggesting group differences in sensory processing in the left hemisphere. The right N1 mean and peak amplitudes were also larger for incongruent trials (mean amplitude: –2.51 μV, peak amplitude: –5.02 μV) compared to congruent trials (mean amplitude: –2.34 μV, peak amplitude: –4.84 μV) across both groups, suggesting greater sensory processing occurred on incongruent trials compared to congruent trials for both the mindfulness and active control training groups. There were no other significant effects observed for the N1 waveform at the left or right cluster (all *p* values > .077 and .052, respectively).

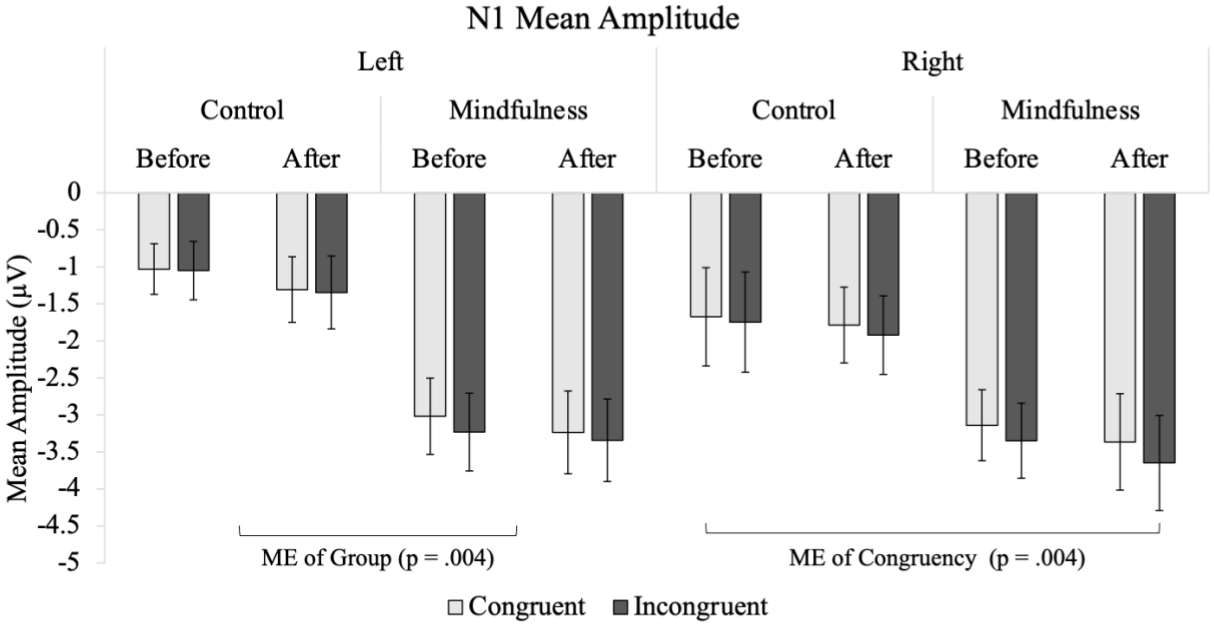

Figure 9. N1 mean amplitudes organized by hemisphere (left electrode clusters: PO7, PO5; right clusters: PO8, PO6) in microvolts (μV) (**A**) collapsed across congruency and time for control and mindfulness groups and (**B**) collapsed across group and time for congruent trials and incongruent trials. Overall, there was a main effect of group in the left hemisphere where the N1 mean amplitude was larger for the mindfulness group than the control group (p = .004) and a main effect of congruency in the right hemisphere where the N1 mean amplitude was larger for incongruent than congruent trials in the right hemisphere (p = .004). Error bars represent standard errors.

N2 at FCz (250 to 350 ms)

The N2 waveform at the FCz electrode site is depicted in Figure 10. Mixed repeated measures ANOVAs revealed significant effects for the N2 mean amplitude, peak amplitude and peak latency within a time window of 250 to 350 ms after stimulus onset. There was a significant main effect of *Congruency* [*F*(1,33) = 9.72, *p* = .004] and a significant *Time x Congruency x*

Group interaction [*F*(1,33) = 4.47, *p* = .042] for the N2 mean amplitude. No other significant main effects or interactions were observed for the N2 mean amplitude (all *p* values > .255). Overall, the N2 mean amplitude was significantly larger for incongruent than congruent trials. Post-hoc pairwise comparisons of the *Time x Congruency x Group* interaction showed that the N2 mean amplitude for the mindfulness group was significantly different on congruent and incongruent trials before training (congruent before = –.95 μV, incongruent before = –1.33 μV, *p* = .002), but this difference did not exist after training (congruent after = –.92 μV, incongruent after = –1.08 μV, *p* = .127), suggesting increased efficiency in conflict detection and monitoring of stimuli with varying degrees of cognitive interference after mindfulness training. There were no other significant post-hoc pairwise comparisons for this *Time x Congruency x Group* interaction (all *p* values > .099).

There was also a significant main effect of *Congruency* for the N2 peak amplitude [*F*(1,33) = 4.79, *p* = .036], where the peak amplitude was significantly larger for incongruent than congruent trials (congruent = –2.06 , incongruent = –2.21, *p* = .036). No other significant main effects or interactions for the N2 peak latency were observed (all *p* values > .122).

There was also a significant *Congruency x Group* interaction for the N2 peak latency, [*F*(1,33) = 4.54, *p* = .041]. Post-hoc pairwise comparisons showed that overall, the mindfulness group had a significant difference in congruency of the N2 peak latency (mindfulness congruent = 293.69 ms, mindfulness incongruent = 300.68 ms, *p* = .028), while there was no difference in the control group (control congruent = 300.17 ms, control incongruent = 297.55 ms, *p* = .435). The N2 peak latency between groups was not significantly different on congruent (*p* = .426) or incongruent trials (*p* = .696). There were no other significant effects were observed for the N2 peak latency (all *p* values > .113).

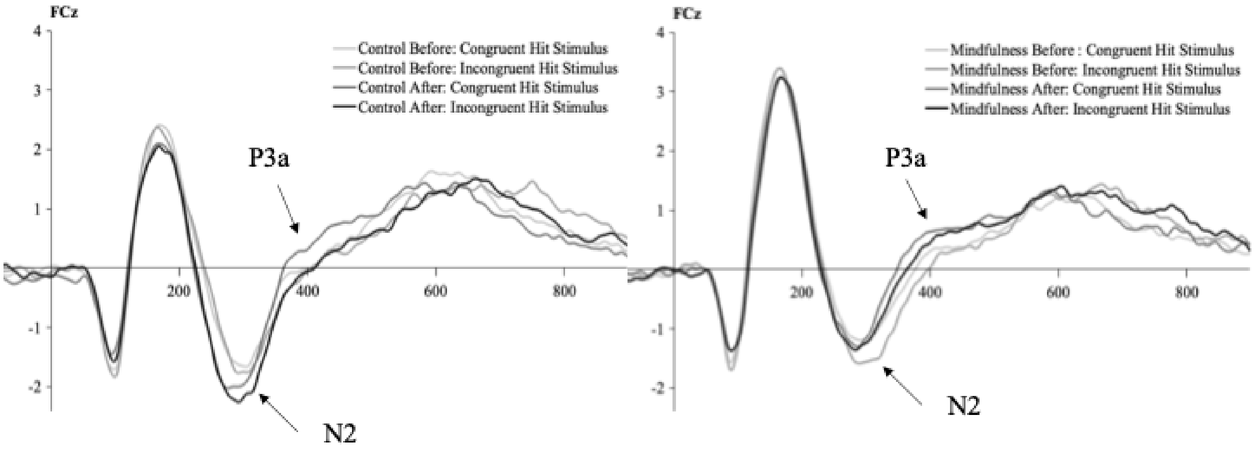

Figure 10. N2 (250-350 ms) and P3a (325-425 ms) ERPs are depicted at FCz for the control group before and after (left panel) and the mindfulness group before and after (right panel). Overall, N2 mean and peak amplitudes were larger for incongruent trials than congruent trials and larger after training for both groups. N2 peak latencies were also significantly faster after training in both groups. Post-hoc pairwise comparisons of a significant Time x Congruency x Group interaction ($p = .042$) showed that the N2 mean amplitude for the mindfulness group was significantly different on congruent and incongruent trials before training ($p = .002$), but this difference in conflict detection and monitoring of congruency dissipated after training ($p = .127$). P3a amplitudes were larger for congruent trials than incongruent trials. Post-hoc pairwise comparisons of a significant Time x Congruency x Group interaction ($p = .041$) for the P3a latency also showed that after training, P3a peak latencies on incongruent trials were significantly slower for the mindfulness group compared to the control group ($p = .049$) and compared to congruent stimuli ($p = .013$). No significant differences were observed in the control group after training.

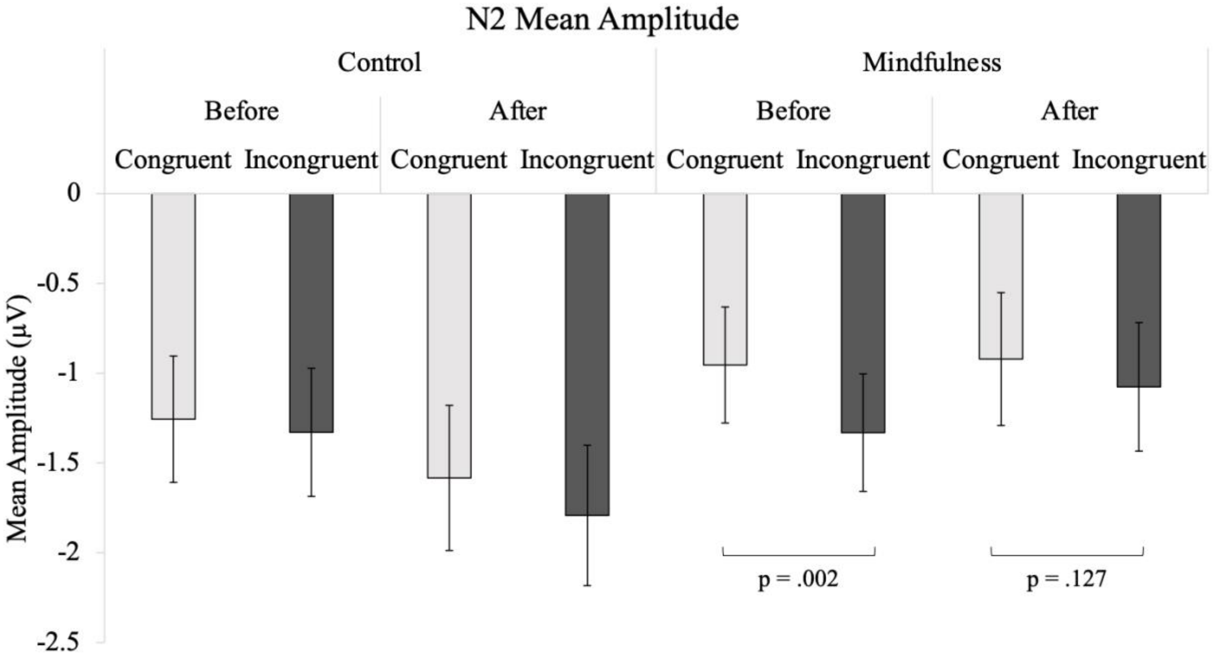

Figure 11. N2 mean amplitudes at FCz in microvolts (µV) for control and mindfulness groups organized by time and congruency with a latency window of 250 to 350 ms. Overall, the N2 amplitude was larger for incongruent trials than congruent trials p = .004). Before training, the N2 mean amplitude in the mindfulness group was significantly different for congruent and incongruent trials (p = .002), but this difference was eliminated after training (p = .127). N2 mean amplitudes showed the same pattern of results. Error bars represent standard errors.

P3a at FCz (325 to 425 ms)

The P3a waveform at the FCz electrode side is depicted in Figure 10. Mixed repeated measures ANOVAs revealed significant effects for the P3a mean amplitude, peak amplitude and peak latency within a time window of 325 to 425 ms. There was a significant main effect of *Congruency* for the mean amplitude [*F*(1,33) = 15.61, *p* < .001] and the peak amplitude [*F*(1,33) = 6.997, *p* = .012] where the amplitudes were significantly larger for congruent than incongruent trials. There was also a significant main effect of *Congruency* [*F*(1,33) = 5.05, *p* = .031] and a significant *Time x Congruency x Group* interaction for the P3a peak latency [*F*(1,33) = 4.55, *p* = .041]. Overall, the P3a peak latency was significantly faster for congruent trials than incongruent trials (congruent = 391.87 ms, incongruent = 398.24 ms). Post-hoc pairwise comparisons of the

Time x Congruency x Group interaction showed that after training, P3a peak latency for the mindfulness group was significantly slower on incongruent trials than for the control group (mindfulness after incongruent = 404.61 ms, control after incongruent = 388.92 ms, *p* = .049). After training, this delayed incongruent P3a peak latency in the mindfulness group was also significantly slower than the P3a peak latency on congruent trials (mindfulness after congruent = 387.34 ms, mindfulness after incongruent = 404.61, *p* = .013), while no difference in congruency of peak latency was observed in the control group (control after congruent = 394.29 ms, control after incongruent = 388.92 ms, *p* = .460). This suggests a congruency effect in the speed of stimulus evaluation after mindfulness training where there was a significant delay in stimulus-driven attentional capture of incongruent stimuli compared to congruent stimuli, but not after active control (guided visual) training. No other significant effects were observed for the P3a mean amplitude (all *p* values > .154), peak amplitude (all *p* values > .113), or peak latency (all *p* values > .189).

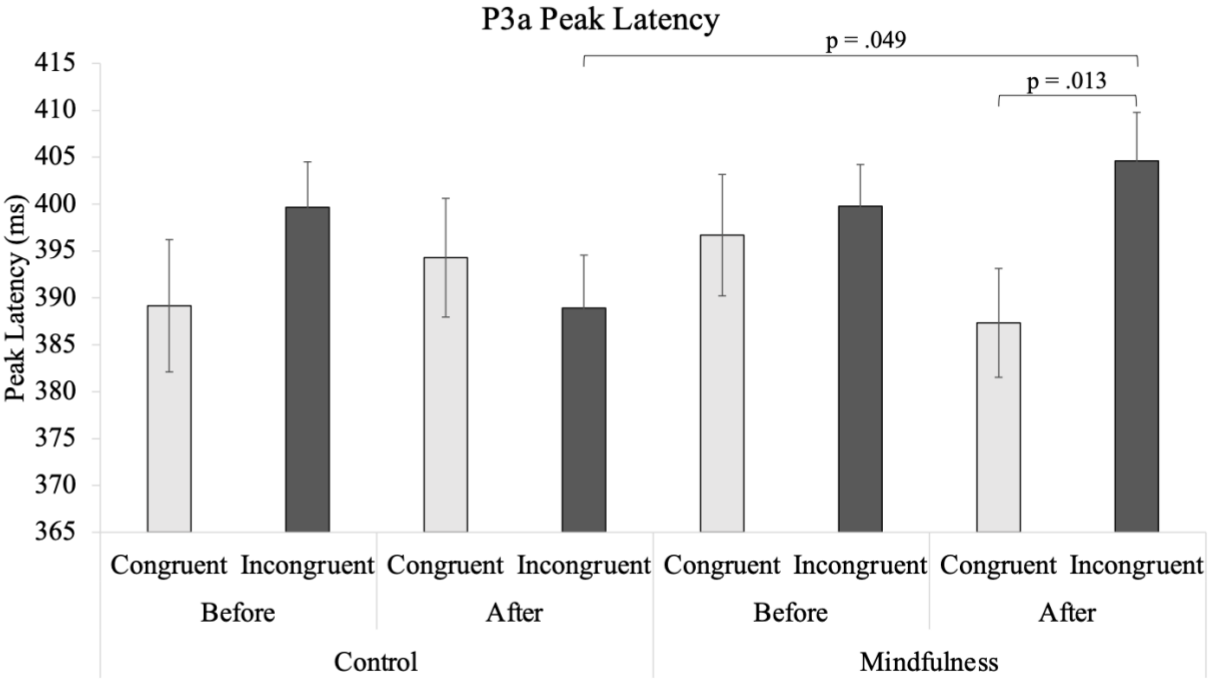

Figure 12. P3a peak latencies at FCz in milliseconds (ms) for control and mindfulness groups organized by congruency, before and after training, with a latency window of 325 to 425 ms. After training, P3a peak latency for the control group was significantly faster on incongruent trials than the mindfulness group (p = .049). After training, this delayed incongruent P3a peak latency in the mindfulness group was also significantly slower than the P3a peak latency on congruent trials (p = .013). Error bars represent standard errors.

P3b at Pz (250 to 550 ms)

The P3b waveform at the Pz electrode site is depicted in Figure 13. Mixed repeated measures ANOVAs revealed a significant main effect of *Congruency* for the P3b mean amplitude [$F(1,33) = 36.37$, $p < .001$], peak amplitude [$F(1,33) = 16.62$, $p < .001$] and peak latency [$F(1,33) = 10.18$, $p = .003$]. Overall, amplitudes were larger and slower for congruent than incongruent trials. There was also a significant *Time x Group* interaction for the P3b peak amplitude [$F(1,33) = 5.90$, $p = .021$]. Post-hoc pairwise comparisons showed that after training, the mindfulness group had a significantly earlier peak latency compared to their baseline (mindfulness before = 338.97 ms, mindfulness after = 323.96 ms, $p = .014$), and compared to the control group post-training (mindfulness after = 323.96 ms, control after = 341.19 ms, $p = .020$), suggesting faster conscious evaluation of all stimuli after mindfulness training. There were no significant differences between groups before training (*p* = .649) or within the control group before and after training (*p* = .372). No other significant effects were observed for the mean amplitude (all *p* values > .326), peak amplitude (all *p* values > .141), or peak latency (all *p* values > .252).

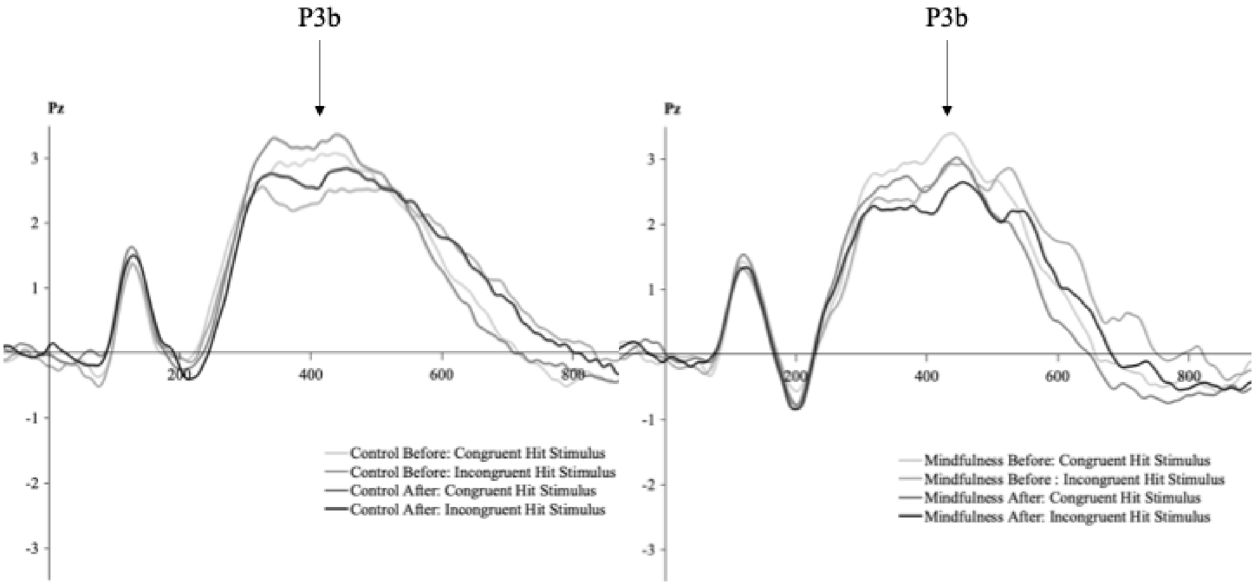

Figure 13. P3b ERPs are depicted at Pz with a time latency window of 250 to 550 ms for control group before and after (left panel) and mindfulness group before and after (right panel). Overall, P3b mean and peak amplitudes were larger for congruent trials than incongruent trials. Post-hoc pairwise comparisons of a significant Time by Group interaction (p = .021) showed that P3b peak latencies were significantly earlier in the mindfulness group after training compared to baseline (p = .014) and compared to the control group after training (p = .020).

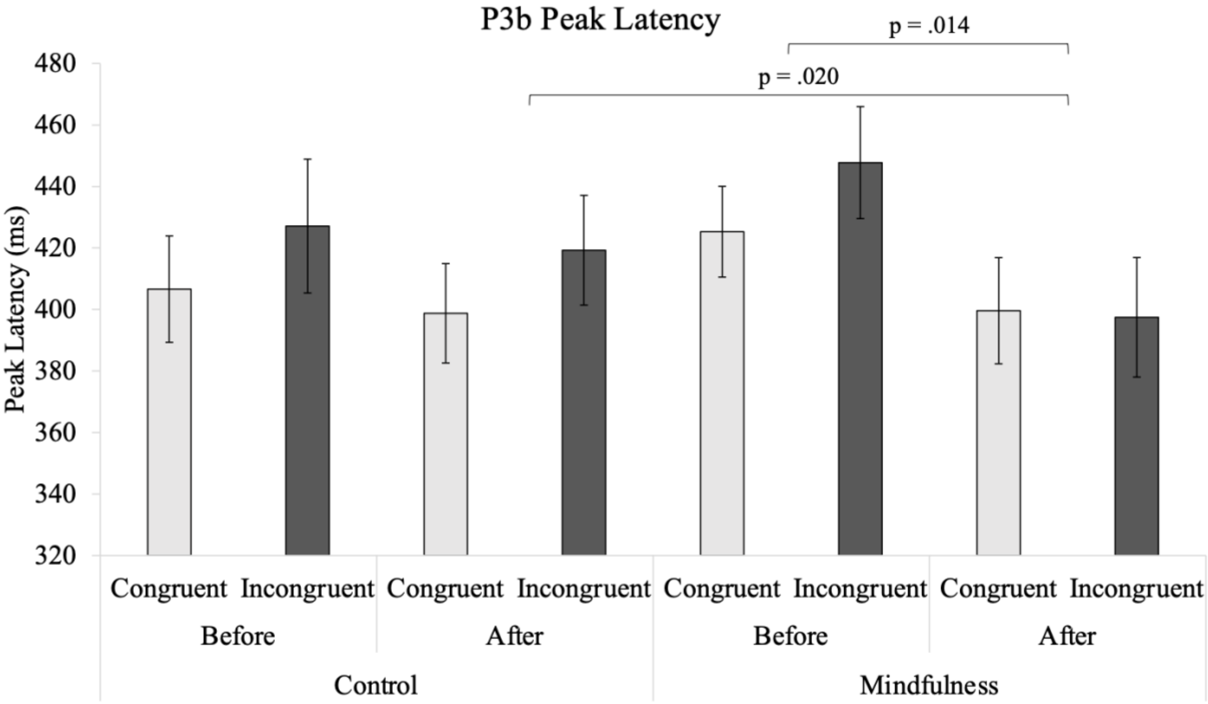

Figure 14. P3b peak latencies at Pz in milliseconds (ms) for control and mindfulness groups organized by congruency, before and after training, with a latency window of 250 to 550 ms. Overall, P3b peak latencies were significantly earlier in the mindfulness group after training (p = .014). After training, P3b peak latencies in the mindfulness group are significantly faster than P3b peak latencies in the control group (p = .020). Error bars represent standard errors.

ERN at FCz (0 to 75 ms)

The ERN waveform at the FCz electrode site is depicted in Figure 15. Mixed repeated measures ANOVAs revealed significant effects for the peak amplitude and peak latency within a time window of 0 to 75 ms after response, but no significant main effects for mean amplitude were observed (all *p* values > .104). There was a significant *Congruency x Group* interaction for the ERN peak amplitude [*F*(1,33) = 6.47, *p* = .016], but no other significant effects were observed for this measure (all *p* values > .168). Post-hoc pairwise comparisons showed the peak amplitude was significantly larger for congruent errors than incongruent errors, consistent with what would be expected in a Stroop task, but only for the mindfulness group (mindfulness congruent = –2.33 μV, mindfulness incongruent = –1.65 μV, *p* = .009); there was no significant difference in ERN by congruency for the control group (control congruent = –1.84 μV, congruent incongruent = –2.09 μV, *p* = .366). There was also a significant main effect of *Congruency* for the ERN peak latency [*F*(1,33) = 6.54, *p* = .015], where the ERN peak latency was significantly slower after congruent errors than incongruent errors, and a significant *Time x Group* cross-over interaction for the peak latency [*F*(1,33) = 5.37, *p* = .027]. Post-hoc pairwise comparisons showed that the ERN peak latency for the mindfulness group was significantly earlier than that observed in the control group before training (mindfulness before = 23.75 ms, control before = 33.69 ms, *p* = .005), but the ERN peak latency was not significantly different between groups after training (mindfulness after = 31.04 ms, control after = 26.98 ms, *p* = .434), suggesting delayed automatic detection of errors after mindfulness training. No other significant effects for the ERN peak latency were observed (all *p* values > .096).

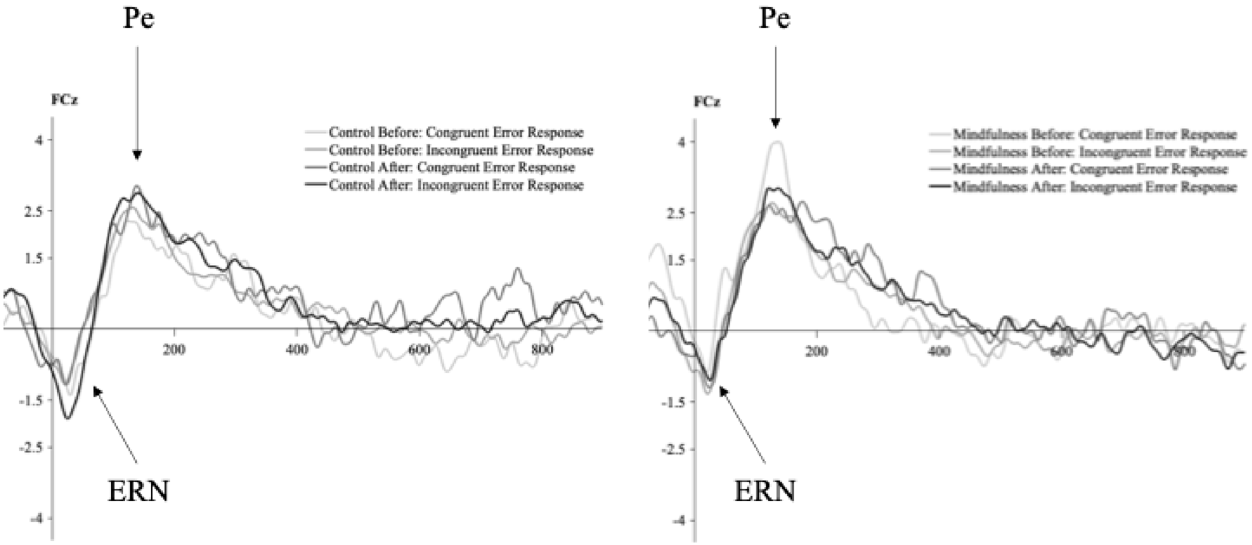

Figure 15. The error-related negativity (ERN: 0 to 75 ms) and error positivity (Pe: 100 to 200 ms) are depicted at FCz for the control group before and after (left panel) and the mindfulness group before and after (right panel). Overall, post-hoc pairwise comparisons of a significant Congruency x Group interaction (p = .016) showed that the ERN peak amplitudes were significantly larger for congruent errors than incongruent errors but only for the mindfulness group (p = .009). Overall, the ERN peak latency was significantly slower for congruent errors than incongruent errors (p = .015). Post-hoc pairwise comparisons of a significant Time x Group interaction (p = .027) also showed that the ERN peak latency for the mindfulness group was significantly earlier than the control group before training (p = .005), but not significantly different after training (p = .434). Overall, the Pe peak amplitude was significantly larger for congruent errors than incongruent errors (p = .038), but no other significant effects for the Pe were observed.

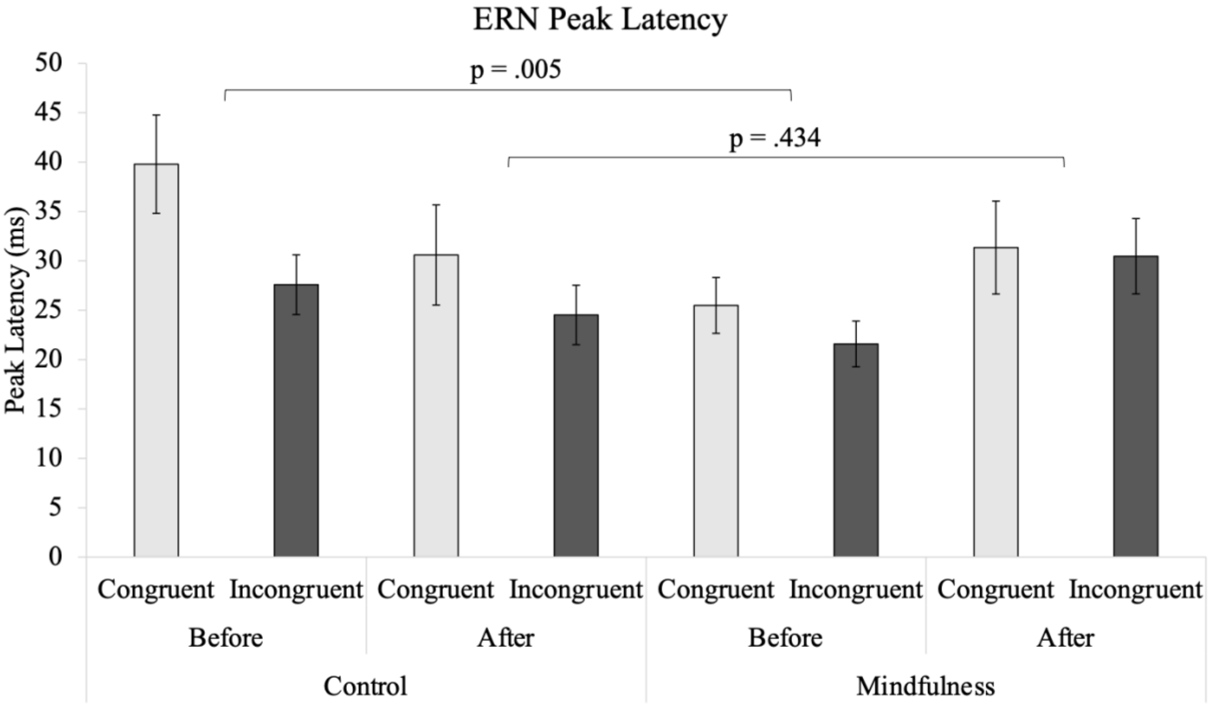

Figure 16. ERN peak latencies at FCz in milliseconds (ms) for control and mindfulness groups organized by congruency, before and after training, with a latency window of 0 to 75 ms. Post-hoc pairwise comparisons of a significant Time by Group interaction (p = .027) revealed that the ERN peak latency for the mindfulness group was significantly earlier than the control group before training (p = .005), but not significantly different after training (p = .434). Overall, the ERN peak latency was significantly slower on congruent errors than incongruent errors (p = .015). Error bars represent standard errors.

Pe at FCz (100 to 200 ms)

The Pe waveform at the FCz electrode site is depicted in Figure 15. Mixed repeated measures ANOVAs revealed a significant main effect of *Congruency* for the Pe peak amplitude within a time window of 100 to 200 ms after response [$F(1,33) = 4.65$, $p = .038$). Overall, the Pe peak amplitude was significantly larger for congruent than incongruent trials (congruent = 4.68 μV, incongruent = 4.34 μV, $p = .038$), indicating greater affective salience of errors made on the "easier" congruent trials. No significant effects were observed for the Pe mean amplitude or Pe peak latency (all p values > .120).

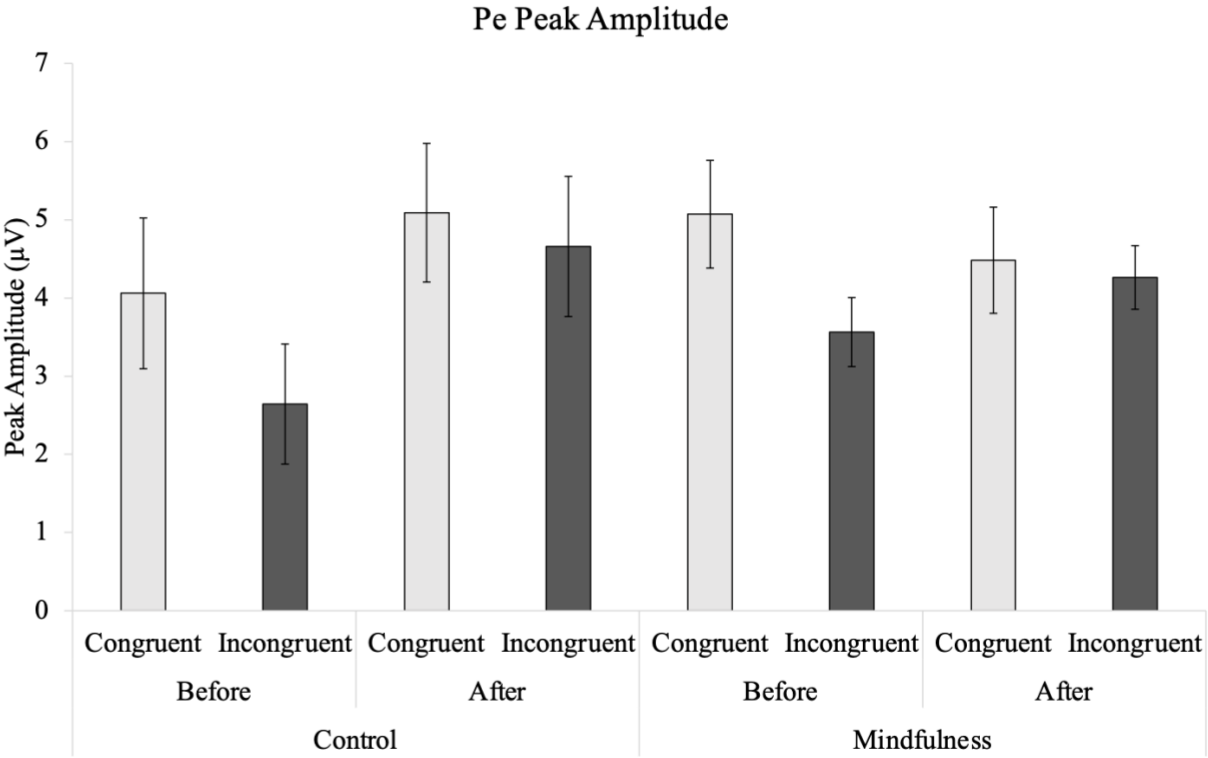

Figure 17. Pe peak amplitudes at FCz in milliseconds (ms) for congruent and incongruent errors organized by time, before and after training, with a latency window of 100 to 200 ms. Overall, Pe peak amplitudes were larger for congruent errors than incongruent errors (p = .038). Error bars represent standard errors.

Discussion

In the current electrophysiology literature, it is difficult to interpret the effects of mindfulness training on neurophysiological indices of attention and cognitive control in the absence of carefully controlled longitudinal designs that establish an information processing timeline using both stimulus-locked and response-locked ERPs. By isolating the specific effects of mindfulness training using ERPs associated with enhanced attention and cognitive control, we can capture an electrophysiological time course of cognitive processes that are unique to mindful attention regulation. Establishing this information processing timeline is important when studying the impact of mindfulness on underlying neural correlates of early sensory processing sensitive to selective attention, conflict monitoring, allocation of attentional resources, conscious stimulus evaluation and response selection, as well as reactivity to errors.

EEG was used to record ongoing neural activity during performance of the Digit Stroop task, before and after two weeks of daily mindfulness meditation practice or guided visual imagery practice. By contrasting the passive attention regulation in guided visual imagery meditation with the more controlled and specific practice of sustaining focus, disengaging from distractions and re-directing attention in mindfulness meditation, the results of this study isolated electrophysiological indices of cognitive control unique to mindful attention regulation. After two weeks of daily practice, the mindfulness meditation group showed multiple electrophysiological changes, including increased efficiency in conflict detection and monitoring of stimuli with varying degrees of cognitive interference (attenuated N2 amplitude), delayed automatic capture of attention by incongruent stimulus features (delayed P3a latency for incongruent stimuli), faster conscious evaluation of all stimuli (earlier P3b latency), and delayed automatic detection of errors (delayed ERN latency).

N2: Conflict Detection, Conflict Monitoring and Inhibition

The current study provides evidence that mindfulness training may increase efficiency in control processes related to conflict detection, conflict monitoring and inhibitory suppression of incorrect responses. Before training, the mindfulness group showed a larger front-central N2 mean amplitude for incongruent compared to congruent trials. However, this baseline difference in conflict detection and monitoring for incongruent versus congruent stimuli was eliminated after mindfulness training, suggesting the same recruitment of control processes were required to detect, monitor and inhibit conflict in both congruent and incongruent stimulus features. In other words, this finding suggests that mindfulness training may optimize the deployment of control processes related to conflict detection, monitoring and inhibition in order to process stimuli with varying degrees of cognitive interference more efficiently. Overall, the mindfulness group also had an earlier N2 peak latency on congruent trials compared to incongruent trials, before and after training. This suggests that the neural processes involved in identifying conflict occurred more quickly on congruent trials versus incongruent trials for the mindfulness group, even though the neurocognitive resources required to process varying degrees of conflict was attenuated and not significantly different from the active control group after training.

This result is divergent from a small set of prior mindfulness ERP studies that found increased N2 amplitudes during cognitive control tasks (Atchley et al., 2016; Malinowski et al., 2017; Moore et al., 2012; Norris et al., 2018; Quaglia et al., 2016). In two very different longitudinal mindfulness training studies that also used a Stroop-like paradigm, an increase in N2 amplitude was observed post-intervention (Malinowski et al., 2017; Moore et al., 2012), however, it is unclear the extent to which methodological differences may have contributed. Malinowski et al. (2017) compared performance on an emotional-counting Stroop task in a group of older adults (ages 55 to 75 years) after 8 weeks of mindfulness meditation training or brain training exercises (active control), while Moore et al. (2012) examined performance on a colour-word Stroop task in a group of healthy adults with 16 weeks of mindfulness meditation training compared to wait list controls. While both studies used a substantially longer length of training relative to our 2 weeks of training, importantly, Malinowski et al. (2017) studied a sample of older adults who are likely to demonstrated a greater prevalence of age-related executive deficits (Friedman et al., 2009; Friedman & Robbins, 2022) and therefore may have had more room to improve on a task designed to recruit executive control and emotion regulation simultaneously that would be more likely to elicit an increased N2 response. On the other hand, Moore et al.

(2012) compared colour-word Stroop performance after 16 weeks of mindfulness training using a population of healthy younger adults and observed an increased N2 response on incongruent trials. Taken together, the results of these studies suggest that a longer period of mindfulness training may be required to observe an increased N2 amplitude, particularly on incongruent trials. However, the N2 reported by Malinowski et al. (2017) peaked between 160 and 240 ms over occipital-parietal regions of both hemispheres and better fits the profile of an N1 component, rather than an N2 component. Finally, both prior Stroop studies employed control groups very different from the active control group included in the present study. Therefore, increased N2 amplitudes may only be observed relative to control conditions that do not have comparable demands on cognitive control.

P3a: Stimulus-Driven Attentional Capture and Involuntary Allocation of Attention

In line with our hypotheses, the mindfulness group exhibited resistance to automatic capture of stimulus-driven attention after training, particularly to incongruent stimuli, reflected by a slower P3a peak latency on incongruent stimuli compared to congruent stimuli after mindfulness training. This P3a peak latency on incongruent trials in the mindfulness group was also significantly slower than in the control group after training. No significant change in the P3a peak latency between congruency conditions was observed in the control group. This congruency effect in the speed of stimulus-driven attentional capture demonstrates delayed involuntary allocation of attention after mindfulness training, but not after active control training.

To our knowledge, only two prior studies have examined the impact of mindfulness meditation training (?) on the fronto-medial P3a component. In a within-subject design, Cahn and Polich (2009) compared performance on an auditory oddball task after 30 minutes of mindfulness (Vipassana) meditation or 30 minutes of random thinking (mind-wandering) in a sample of meditators with 20 years of Vipassana meditation experience. They observed a lower P3a amplitude for deviant (i.e.., incongruent) tones during the meditative state relative to the mind-wandering state. This size of the reduction in P3a amplitude was also positively correlated with frequency of meditation practice, providing strong evidence that the practice of mindfulness is associated with reduced stimulus-driven attentional capture. While the reduced P3a amplitude associated with detection of deviant or incongruent stimuli in the context of mindfulness practice is limited to this one study of very experienced meditators, a recent study by Incagli and colleagues (2020) examined the impact of 8 weeks of Mindfulness Based Stress Reduction (MBSR) training on cognitive control performance using an AX-continuous performance task (AX-CPT; Dias et al., 2003). Based on Braver et al.'s (2007) theory of Dual Mechanism of Cognitive Control (DMCC), the AX-CPT paradigm was used to test the dynamic interaction between proactive (e.g., give example of what ERP would measure proactive) and reactive (e.g., what ERP measures reactive) cognitive control mechanisms. Increased P3a amplitudes were observed across all trial types after MBSR training relative to the active control training group that received 8 weeks of Pilates training. Although this result is opposite to the attenuated P3a amplitude observed in the study by Cahn and Polich (2009), larger P3a amplitudes have been observed in AX-CPT paradigms and are thought to reflect greater inhibition of prepotent responses (Morales et al., 2015). Therefore, this larger P3a amplitude was interpreted as increased efficiency of reactive cognitive control mechanisms in the MBSR group post-training.

Although we did not observe modulations of P3a amplitude after mindfulness training, the delay in P3a peak latency on incongruent trials demonstrates a disengagement of automatic stimulus-driven attentional capture similar to what was found by Cahn and Polich (2009). This interpretation of the present P3a latency finding is in line with Verdonk et al.'s (2020) view that mindfulness facilitates unbiased information processing by disengaging the attentional system from stimulus-driven activation. It is important to note however that the attenuated P3a amplitude for deviant tones reported by Cahn and Polich (2009) was observed in experienced meditators during a meditative state, while our delayed P3a peak latency was observed in naive meditators after 2 weeks of daily meditation during a cognitive control task. Even though Incagli et al. (2020) also examined cognitive control performance after mindfulness training, the duration of MBSR training lasted 8 weeks and was compared to an active control group (Pilates training) that placed emphasis on performing correct and harmonious movements. During a typical MBSR program, individuals follow a structured and standardized intervention that includes a variety of attention regulation exercises, including sitting meditation, walking meditation, eating meditation, gentle movement, and body scan (Kabat-Zinn, 1990). Although it is plausible that engaging in an 8-week MBSR program increases domain-general cognitive control overall, without an appropriate active control group to target precise cognitive processes, it is still unclear which mindful attention regulation mechanisms in MBSR lead to increased efficiency of reactive cognitive control mechanisms (reflected by larger P3a amplitudes). Nevertheless, this finding challenges our current interpretation of the delayed P3a peak latency observed in our study. Rather than proactively disengaging the attentional system from stimulus-driven activation, mindfulness training could have upregulated reactive control mechanisms, resulting in a late-correction process. As a result, the delayed P3a peak latency on incongruent trials could reflect reactive control mechanisms that activate “just-in-time” to detect and solve incongruent interference immediately before a response is required in a late correction rather than early detection method of processing.

P3b: Conscious Processing and Evaluation of Stimuli

We also predicted that the deliberate disengagement of attention from task irrelevant features (identity of digits) and redirection of attention to relevant task features (number of digits) would lead to more efficient evaluation and conscious processing of stimuli after mindfulness training, reflected by decreased P3b amplitudes and faster P3b latencies compared to the active control group. Although we did not observe modulation of P3b amplitudes between or within groups across time, the mindfulness group had significantly faster P3b peak latencies on both congruent and incongruent stimuli after training, suggesting faster conscious processing and evaluation of stimuli overall. This effect was not observed in the active control group, who showed no significant difference in latency of the P3b before versus after training.

The impact of mindfulness on the P3b is mixed in the literature. Mindfulness has been associated with greater P3b amplitudes on tests that require attention to task-relevant stimuli, such as the auditory oddball task (Atchley et al., 2016; Delgado-Pastor et al., 2013; Smart et al., 2016). However, mindfulness has also been associated with reduced P3b amplitude during tests that require inhibition of task-irrelevant information, such as distractor tones during an auditory oddball task (Atchley et al., 2016), irrelevant stimuli during an attentional-blink task (Slagter et al., 2007), irrelevant stimuli during a Go/Nogo task (Howells et al., 2012) or competing alternatives during a Stroop task (Moore et al., 2012). Finally, some studies show no effect of mindfulness on the P3b during the Attention Network Task (Norris et al., 2018) or the Stroop task (Malinowski et al., 2017). Furthermore, no prior studies report significant changes to P3b peak latencies after mindfulness training.

In general, across studies in the extant literature, increased P3b amplitude was observed when processing task-relevant stimuli (Atchley et al., 2016; Delgado-Pastor et al., 2013; Smart et al., 2016) and decreased P3b amplitude was observed when inhibition of task-relevant information was required (Atchley et al., 2016; Slagter et al., 2007; Howells et al., 2012; Moore et al., 2012). This pattern supports the differences in P3b findings in the current study, where P3b amplitudes were significantly larger for congruent trials, where both stimulus features (identity of digits and number of digits) activate the correct task-relevant response (number of digits), compared to incongruent trials, which require greater inhibition of task-irrelevant features (identity of digits). While no changes to P3b amplitudes were observed between groups across time, significant differences in P3b peak latencies were observed, reflecting changes to speed of conscious processing and evaluation of stimuli. Surprisingly, we found that P3b peak latencies were significantly faster for incongruent stimuli compared to congruent stimuli overall, suggesting faster allocation of attention to the evaluation and processing of stimuli with greater conflict, and slower allocation of attention involved in evaluation and processing of stimuli with less conflict. While this difference in amplitude and latency across congruency (larger, slower P3b on congruent trials and smaller, faster P3b on incongruent trials) suggests differential recruitment of control processes for each trial type, this pattern was observed in both groups across time and therefore cannot be attributed to any training effects. Instead, it is more likely due to distinct control strategies that are engaged by task stimuli with varying degrees of conflict or cognitive interference. Irrespective of congruency, we still observed a significantly faster P3b peak latency in the mindfulness group after training, which reflects faster conscious processing and evaluation of stimuli overall.

ERN and Pe: Error Processing and Performance Monitoring

Finally, we also hypothesized that the deliberate disengagement of elaborative processing and redirection of attention to present task goals in mindfulness training would facilitate “nonjudgmental acceptance” when errors are committed, leading to attenuated salience and/or conscious awareness of errors after mindfulness training. In line with this, we predicted decreased ERN and Pe amplitudes after mindfulness training and increased ERN and Pe amplitudes after control training, particularly for the more salient congruent errors. However, the mindfulness group showed a significantly larger ERN peak amplitude after errors on congruent trials compared to errors on incongruent trials, suggesting greater reactivity to having made an error on the easier trials, while there were no significant differences in the ERN following errors on congruent versus incongruent trials for the control group. Interestingly, there was a significant Time x Group cross-over interaction that showed the ERN peak latency regardless of stimulus congruency was significantly faster for the mindfulness group than that the control group before training, but there was no difference between groups after training. In other words, this cross-over interaction shows that while the active control group became faster at automatic detection of errors after training, the speed of automatic neural response to errors after mindfulness training was delayed. No difference in ERP markers of conscious error processing were observed between or within groups as measured by the Pe. Overall, Pe peak amplitudes were significantly larger for congruent than incongruent trials across groups, suggesting both groups were consciously processing and equally more aware of committing more salient errors on the “easier” congruent trials compared to incongruent trials both pre- and post-training.

The impact of mindfulness on error detection and performance monitoring is mixed in the literature. Some prior studies have found an increased ERN associated with mindfulness (Teper & Inzlicht, 2013; Smart & Segalowitz, 2017; Eichel et al., 2017; Saunders et al., 2016) while some studies show a decreased or unchanged ERN (Larson et al., 2013; Schoenberg et al., 2014; Bing-Canar et al., 2016). Likewise, the impact of mindfulness on Pe modulation is unclear, with some studies showing an increased amplitude (Schoenberg et al., 2014), some studies showing a decreased amplitude (Larson et al., 2013) while some studies showed no change (Teper & Inzlicht, 2013; Smart & Segalowitz, 2017; Saunders et al., 2016; Bing-Canar et al., 2016).

In the present study, mindfulness training did not modulate ERN or Pe amplitudes. We found that both groups displayed neurophysiological indices suggesting greater affective salience to committing errors on congruent trials relative to incongruent trials, as would be in keeping with the conceptualization of the ERN and Pe broadly, and this did not vary between groups or across time. We did however find group differences across time in the ERN peak latency, irrespective of stimulus congruency. Specifically, the active control group became faster at automatic detection of errors after training while the mindfulness group showed a delayed neural indicator of automatic error detection after mindfulness training. We propose this delay in attentiveness to errors as measured by the ERN was facilitated by the deliberate disengagement of elaborative processing or “judgment” when errors are committed, resulting in decreased vigilance of error detection after mindfulness training. To our knowledge, this is the first study to show differences in ERN latencies after mindfulness training.

General Discussion

Taken together, these electrophysiological results demonstrate key differences in neural markers of cognitive control processes after mindfulness training relative to guided visual imagery training. After mindfulness training, individuals were still faster at processing conflict in congruent stimuli compared to incongruent stimuli, even though the neurocognitive resources required to process varying degrees of conflict was attenuated after training. Following this attenuated conflict detection, the mindfulness group showed a congruency effect in the speed of stimulus-driven attentional capture, demonstrating delayed involuntary allocation of attention to incongruent stimuli in the same focal anterior regions, which was not observed after active control training. The mindfulness group also showed faster conscious processing and evaluation of both congruent and incongruent stimuli overall—an effect that was not observed in the active control group, who showed no significant difference in speed of processing after training. Finally, after committing errors, the mindfulness group demonstrated a delayed automatic neural detection of errors, while the active control group showed the opposite trend.

Despite these group differences in electrophysiological indices of cognitive control, there were no significant differences in behavioural performance between groups after training. Overall, both groups showed the same pattern of expected reduction in response times, the Stroop interference effect, post-error slowing (PES) and increased accuracy. There was a *Congruency x Group* interaction for RT and significant main effect of *Group* for the Stroop interference effect, but this showed that overall, difference in congruency was greater for the active control group. Although this points to pre-existing differences between groups, the difference in congruency collapsed across time suggests differential control mechanisms in the active control group overall. In contrast with mindful attention regulation, it’s possible the passive attention regulation in guided visual imagery training facilitated susceptibility to conflict or interference effects. This is supported by faster involuntary attentional capture by incongruent stimuli relative to congruent stimuli, and slower conscious evaluation and processing of all stimuli observed in the active control training group.

Limitations and Future Directions

Due to scheduling constraints and limited enrollment of the four in-person group training sessions, our experiment consisted of small sample sizes. Smaller sample sizes introduced more individual variance in the mean ERP data, placing emphasis on within group differences rather than between group differences when pre-existing group differences emerged in the data. As part of this larger longitudinal design, participants also completed a number of different tasks at baseline and after two weeks of daily training. Therefore, it’s possible the current results are confounded by states of fatigue and decreased attentional vigilance, particularly post-training, when we expect the largest impact of mindfulness training on cognitive control. While this potential effect would be similar across training groups, it could have impacted the comparison of the present results to prior studies reported in the literature.

In order to completely isolate and discern the effects of mindfulness training on cognitive control, it is necessary to contrast mindful attention regulation and passive attention regulation with an inactive control group that doesn’t engage in any kind of attention regulation training between pre-test and post-test sessions. Although we predicted the deliberate exercise of disengaging and redirecting attention in mindfulness training would target specific cognitive control processes, it’s possible that the passive attention regulation in guided visual imagery training also influenced the same cognitive control processes by virtue of simply guiding attention in some way. In other words, without the inclusion of an inactive control group, we can’t confirm whether the guided visual imagery training influenced the same electrophysiological indices of cognitive control in parallel or opposite ways. This could explain why the majority of electrophysiological effects observed in this study reflected changes in speed of processing (peak latencies) rather than modulations in allocation of resources (mean and peak amplitudes), which is more commonly reported in the literature.

While future longitudinal designs should consider the inclusion of an inactive control, subsequent training studies should replicate this design by using passive attention regulation in an active control group to isolate the impact of mindful attention regulation on various ERPs related to cognitive control. While this can be accomplished by using various tasks of executive function, differences in mindfulness may not be observed unless cognitive control processes are sufficiently challenged, contributing to discrepant findings in the mindfulness literature. One way to counteract this is by increasing difficulty on a task such as the titrated Digit Stroop task (Chapter Two) and examining the impact of mindfulness training on behavioural and electrophysiological correlates when cognitive control processes are upregulated.

Conclusion

Using the high temporal resolution of electroencephalography, this study sought to isolate precise neural mechanisms underlying the impact of mindfulness training on various aspects of cognitive control by capturing an information processing timeline linked to both stimulus presentation and response completion. The inclusion of an active control group specifically designed to isolate the effects of mindfulness by contrasting mindful attention regulation with passive attention regulation was fundamental in producing novel results that expand the limited literature on the electrophysiology of mindfulness and cognitive control. Using EEG to record both stimulus-locked and response-locked ERPs, this study provides evidence that after two weeks of daily 20-minute practice, mindfulness training can lead to multiple electrophysiological changes, reflecting efficiency in detecting and monitoring varying degrees of conflict (equivalent N2 amplitudes across congruency), resistance to automatic capture of attention by incongruent stimulus features (delayed P3a amplitude for incongruent stimuli), faster conscious evaluation of all stimuli (earlier P3b latencies), and delayed automatic detection of errors (delayed ERN latencies). The results of this study have important implications for our empirical understanding of mechanisms involved in mindful attention regulation and their convergence with domain-general executive functioning and cognitive control.

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Chapter 4—The Impact of Mindfulness Training on Electrophysiological Indices of Cognitive Control When Task Difficulty is Increased

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Abstract

Few electrophysiological studies examine the effects of mindfulness training on neural indices of enhanced attention and cognitive control. Of these few, large discrepancies in experimental design have led to conflicting results. Here, we address these discrepancies by examining both stimulus-locked and response-locked ERPs in a sample of healthy, young adults, comprised of a mindfulness training group and a novel active control group using a titrated Digit Stroop cognitive control task designed to increase difficulty. Although we did not observe any behavioural differences between groups after training, we found electrophysiological differences that reveal the impact of mindfulness training on early perceptual processing, stimulus-driven attentional capture, and conscious evaluation of stimuli. After two weeks of daily practice, the mindfulness meditation group showed a larger occipital-parietal P1 amplitude in the right hemisphere, reflecting enhanced sensory processing, and earlier posterior P3b peak latencies on congruent and incongruent trials, reflecting faster conscious evaluation of all stimuli. In contrast, the frontal P3a peak latency was significantly delayed in the active control group, while there was no change observed in the mindfulness group, reflecting a resistance to automatic capture of stimulus-driven attention after mindfulness training when task demands were sufficiently challenging. These electrophysiological changes are discussed in terms of the cognitive control processes that vary as a function of mindfulness attention regulation.

Introduction

Broadly conceptualized as present-centered and non-judgmental awareness, mindfulness involves maintaining meta-cognitive awareness of current experiences by sustaining attention on relevant information, ignoring or inhibiting irrelevant information, while monitoring and disengaging from any elaborative processing or judgment that arises in awareness (Bishop et al., 2004; Kabat-Zinn, 1990). Although mindfulness has been practiced for 2,500 years as a deliberate exercise in observing internal and external events or experiences, modern scientific inquiry of mindfulness is relatively recent. Yet, in the span of a few decades, widespread scientific interest in mindfulness has already documented various salutary effects of mindfulness on neurobiological, psychological, and behavioural outcomes. As a deliberate exercise involving attention, an emerging body of literature has examined the convergence between mindfulness and attention-related constructs—most notably executive functions including cognitive control. Cognitive control refers to the set of processes that monitors and selects information relevant to current goals, while ignoring or inhibiting irrelevant information, and facilitating information processing and behaviour to vary adaptively from moment to moment depending on those chosen goals (Botvinick et al., 2001; Cohen et al., 2000; Morton et al., 2011; Posner et al., 2004). By monitoring and selecting information relevant to the present experience and redirecting attention from irrelevant information (e.g., distractions), meditators can develop greater control over a set of cognitive processes that promote useful behavioural adaptations in response to fluctuations in cognitive demand.

Indeed, several studies have documented the impact of mindfulness on executive function (Jha et al., 2007; Moore & Malinowski, 2009; Semple, 2010; Teper & Inzlicht, 2013; see Gallant, 2016 and Chiesa et al., 2011 for reviews). The most consistent findings belong to behavioural studies that have examined the effects of mindfulness training on cognitive control using stimuli that present competing streams of information, such as the Stroop task (Allen et al., 2012; Chan & Woollacott, 2007; Moore & Malinowski, 2009; Teper & Inzlicht, 2013; Wenk-Sormaz, 2005). However, other behavioural studies using similar tasks of executive function showed no significant impact of mindfulness training on cognitive control performance (*Stroop:* Anderson et al., 2007; Moore et al., 2012; *Flanker:* Larson, et al., 2013), leading to discrepant findings and cautious interpretations of underlying mechanisms.

More recently, an emerging literature of electrophysiological studies has attempted to disentangle discrepant findings by using the high temporal resolution of electroencephalography (EEG) and event-related potentials (ERPs) to examine the neural basis of mindfulness and cognitive control. For example, a number of studies have shown that mindfulness is associated with an increase in control processes related to conflict detection and monitoring of competing stimulus features, indexed by an increased anterior N2 ERP amplitude (Atchley et al., 2016; Malinowski et al., 2017; Moore et al., 2012; Norris et al., 2018; Quaglia et al., 2015). Mindfulness has also been linked to modulations of involuntary stimulus-driven attentional capture, indexed by a reduced P3a amplitude to deviant tones in experienced meditators during an auditory oddball task (Cahn and Polich, 2009) and increased efficiency of reactive control mechanisms, indexed by larger P3a amplitudes during the AX-continuous performance task (AX-CPT) after 8 weeks of Mindfulness Based Stress Reduction (MBSR; Kabat-Zinn, 1990; Incagli et al., 2020). There is also evidence that mindfulness is associated with increased conscious access or conscious processing of stimuli during tasks that require attention to task-relevant stimuli, indexed by a larger P3b amplitude on the auditory oddball task (Atchley et al., 2016; Delgado-Pastor et al., 2011; Smart et al., 2016) and reduced P3b amplitude during tasks that require inhibition of task-irrelevant information, such as distractor tones during an auditory oddball task (Atchley et al., 2016), irrelevant stimuli during an attentional-blink task (Slagter et al., 2007), irrelevant stimuli during a Go/Nogo task (Howells et al., 2012) or competing alternatives during a Stroop task (Moore et al., 2012). When examining neural processing during cognitive control tasks when errors are committed, the impact of mindfulness on ERP indices of error monitoring and performance evaluation are mixed in the literature. While some studies showed increased attentiveness to errors associated with mindfulness, indexed by an increased error-related negativity or ERN (Eichel et al., 2017; Saunders et al., 2016; Smart & Segalowitz, 2017; Teper & Inzlicht, 2013), other studies showed decreased or no change in the ERN (Bing-Canar et al., 2016; Larson et al., 2013; Schoenberg et al., 2014). Similarly, some mindfulness studies reported increased conscious processing or evaluation of error, indexed by a larger error positivity or Pe (Schoenberg et al., 2014), other studies showed a reduced Pe (Larson et al., 2013) and even more show no change at all (Bing-Canar et al., 2016; Saunders et al., 2016; Smart & Segalowitz, 2017; Teper & Inzlicht, 2013). While the number of mindfulness ERP studies are quickly increasing, the precise neural mechanisms underlying the impact of mindfulness on different aspects of executive function and cognitive control are difficult to interpret due to large discrepancies in experimental design and their conflicting findings. For example, some cross-sectional studies have examined the impact of long-term mindfulness practice in experienced meditators (Atchley et al., 2016; Teper & Inzlicht, 2013), while other cross-sectional designs have examined the impact of brief mindfulness induction in naive meditators (Bing-Canar et al., 2016; Larson et al., 2013; Norris et al., 2018; Saunders et al., 2016), characterizing two extremes of mindfulness expertise and their impact on cognitive control. Other electrophysiological studies have used expert meditators in a within subject design to examine changes to ERPs during meditative states versus mind-wandering states (Cahn & Polich, 2009; Delgado-Pastor et al., 2013), while other ERP studies have operationalized and measured mindfulness as an inherent disposition using psychometric assessments to categorize participants into groups of high mindfulness and low mindfulness based on a median split (Eichel et al., 2017; Quaglia et al., 2016). These differences in experimental design highlight the importance of carefully controlled longitudinal studies that examine changes to electrophysiological correlates of cognitive control, before and after mindfulness training.

Currently, longitudinal electrophysiological studies that investigate the effects of mindfulness training on cognitive control are very limited. Of these few, no EEG studies using ERPs: 1) establish a cognitive processing timeline using both stimulus-locked and response-locked ERP components, 2) use an appropriate control group that contrasts components of mindful attention regulation, or 3) use tasks that are designed to challenge cognitive control demands. To our knowledge, no studies document both stimulus-locked and response-locked ERPs within a longitudinal design using a population of healthy younger adults. Although Schoenberg et al. (2014) examined the N2, P3, ERN and P3 before and after 12 weeks of Mindfulness Based Cognitive Therapy (MBCT), they compared a clinical sample of individuals with Attention Deficit Hyperactivity Disorder (ADHD) to waitlist controls during a Go/Nogo task and found an increased no-go P3 amplitude and Pe amplitude post-intervention. While this provides some evidence that mindfulness-based interventions can increase conscious access or processing of both stimuli and errors, without the inclusion of an active control group, these post-intervention findings could be a result of practice on the task and may not generalize to cognitive control mechanisms in non-clinical populations.

As an emerging field, this limited electrophysiological mindfulness literature also lacks the use of appropriate control conditions to contrast and isolate the precise cognitive control mechanisms that are distinct to mindfulness training. For example, some studies have compared a mindfulness training group with waitlist controls who do not engage in any training program between testing sessions (Moore et al., 2012; Schoenberg et al., 2014), while other studies have compared mindfulness training with active control groups who are engaging in activities ranging from Pilates training to brain training exercises and psychoeducational training (Incagli et al., 2020; Malinowski et al., 2017; Smart et al., 2017).

Finally, it is not clear whether mindfulness practice always leads to enhanced cognitive control performance. For example, while a number of studies show that mindfulness training is associated with improved cognitive control performance (*Stroop*: Allen et al., 2012; Chan & Wollacott, 2007; Moore & Malinowski, 2009; Teper & Inzlicht, 2013; Wenk-Sormaz, 2005; *ANT*: Tang et al., 2007; Jha et al., 2007), other studies have found little to no behavioural differences after mindfulness training (*Stroop*: Anderson et al., 2007; Josefsson & Broberg, 2011; Moore et al., 2012; Polak 2009; Semple, 2010; *ANT*: Polak, 2009; Flanker: Larson et al., 2013). One possible explanation for this discrepancy is that effects of mindfulness on cognitive performance may not be observable unless task demands are sufficiently challenging. For example, in a previous study we examined whether dispositional mindfulness predicted behavioural performance on an unmodifed (non-titrated) Digit Stroop task compared to a modified (titrated) Digit Stroop task designed to increase difficulty and showed that dispositional mindfulness, measured by the Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003) and the Five-Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006), significantly predicted behavioural indices of cognitive control (decreased Stroop interference and increased accuracy), but only when task difficulty was increased on the titrated variation of the Digit Stroop task (Chapter Two). Without varying demands on cognitive control, effects of mindfulness on behavioural performance may not be observable, contributing to inconsistencies in the literature.

Based on these findings and limitations outlined in the existing literature, in order to examine ongoing neural activity in mindfulness meditators at the time of stimulus presentation and response completion, it's important to establish a cognitive processing timeline by using ERPs in a carefully controlled longitudinal design. The inclusion of an appropriate active control condition is also necessary to isolate the specific effects of mindful attention regulation on ERP markers of enhanced attention and cognitive control. Finally, the effects of mindful attention regulation on cognitive control may not be detected unless those underlying cognitive control mechanisms are experimentally challenged.

Here, we aimed to capture an electrophysiological time course of cognitive control mechanisms associated with mindfulness by examining both stimulus-locked and response-locked ERPs in a mindfulness training group and a novel active control group using a cognitive control task designed to increase difficulty. The Digit Stroop task is a variation of the classic colour-word Stroop task (Stroop, 1935; MacLeod, 1991) where participants are presented with an array of identical digits and instructed to correctly respond to the number of digits while ignoring the identity of the digits. In a recent longitudinal training ERP study (Chapter 3) we showed that mindfulness training was associated with multiple electrophysiological changes underlying performance on the Digit Stroop task including an attenuated N2 amplitude, delayed P3a latency for incongruent stimuli, earlier P3b latencies and delayed ERN latencies, although no differences in behavioural outcomes were observed between groups after training. These findings provide evidence that after two weeks of daily 20-minute practice, mindfulness training can increase efficiency in conflict detection and monitoring of stimuli with varying degrees of cognitive interference (attenuated N2 amplitude), delayed automatic capture of attention by incongruent stimulus features (delayed P3a latency for incongruent stimuli), faster conscious evaluation of all stimuli (earlier P3b latency), and delayed automatic detection of errors (delayed ERN latency), relative to an active control group who engaged in guided visual imagery training.

Our inclusion of an active control group designed to contrast mindful attention regulation with passive attention regulation was fundamental in producing these novel results. Consistent with formal mindfulness training procedures, our mindfulness meditation training instructed individuals to focus their attention internally on the sensations of their breath; observing distracting thoughts, feelings or sensations without judgment or elaboration; and re-directing attention back to their breath. Our active control condition also presented guided training, however, attention was oriented externally to the narration of a nature walk, where elaboration of distracting thoughts, feelings or sensations was embraced with no explicit re-direction of attention to the narration or visualization. Critically, both conditions presented a type of guided meditation, so that the specific training offered by mindfulness meditation could be effectively isolated. Compared to the passive attention regulation in guided visual imagery training, the specific practice of sustaining focus, disengaging from distractions, and re-directing attention in mindfulness meditation was hypothesized to target cognitive control mechanisms and altered neural activity associated with unique changes to ERP markers of attention and cognitive control.

In the present study, we aimed to replicate and extend our previous ERP findings by examining the impact of mindfulness training on both behaviour and electrophysiological mechanisms when the cognitive control system is sufficiently challenged. To vary demands on cognitive control, we manipulated task difficulty by titrating stimulus duration to maintain an accuracy level between 70% and 80%. By increasing task difficulty, we predicted behavioural and electrophysiological outcomes after mindfulness training that reflect enhanced cognitive control. Specifically, we hypothesized that the mindful practice of sustaining focus on relevant task features (number of digits) would facilitate early sensory processing sensitive to selective attention— evident particularly when task demands are challenged— resulting in increased P1 and N1 amplitudes. In line with our previous findings, we also hypothesized that mindfulness training would facilitate greater disengagement from task irrelevant features (i.e., identity of digits), reflected by attenuated N2 amplitudes, while decreasing automatic capture of stimulus-driven attention, reflected by a decreased P3a amplitudes or delayed P3a latencies, particularly on incongruent trials, where there is greater conflict between stimulus features. We also predicted that the deliberate disengagement of attention from task irrelevant features and redirection of attention to relevant task features would lead to more efficient evaluation and conscious processing of stimuli after mindfulness training, reflected by decreased P3b amplitudes and faster P3b latencies (faster processing time) compared to the active control group. Finally, we also hypothesized that the deliberate disengagement of elaborative processing and redirection of attention to present task goals would facilitate “nonjudgmental acceptance” when errors are committed, leading to attenuated vigilance and conscious awareness of errors after mindfulness training. Thus, we predicted decreased amplitudes or delayed latencies in the ERN and the Pe after mindfulness training. Although the impact of mindfulness training on behavioural indices of executive function are inconsistent, we predicted behavioural outcomes that correspond with the hypothesized electrophysiological changes associated with enhanced cognitive control, including faster response times, greater accuracy, reduced Stroop interference, and decreased post-error slowing (PES). Additionally, we used psychometric mindfulness measures to examine how self-reported levels of mindfulness change after training. By manipulating task difficulty and comparing mindfulness training with a novel active control group in a carefully controlled longitudinal design, we sought to isolate the unique effects of mindfulness attention regulation on electrophysiological indices of early sensory processing, conflict detection, stimulus-driven attentional capture, conscious stimulus evaluation and error monitoring.

Methods

Participants

Forty-six undergraduate and graduate students were recruited from online advertisements at McMaster University's Department of Psychology, Neuroscience & Behaviour. Participants were randomly assigned to either a mindfulness group or an active control group. Two participants from the mindfulness group and 5 participants from the active control group dropped out for personal or health reasons unrelated to the study itself. Therefore, final study enrollment included 21 participants (13 female) in the mindfulness group and 18 (14 female) in the active control group. Exclusion criteria included previous meditation experience, uncorrected visual impairment, current or previous diagnosis of psychiatric disorders, neurological disorders, head injury with loss of consciousness, or current use of psychopharmacological treatments. Thus, all participants were neurologically and psychiatrically healthy individuals unpracticed in meditation. All procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Ethics Research Board.

Procedure Overview

This experiment was part of a larger longitudinal training study that consisted of a baseline testing session, two weeks of daily mindfulness or active control training, followed by a final testing session. The order of study procedures was identical between the mindfulness and active control groups and replicates the procedure from our previous study (Chapter 3). During the baseline testing session, all participants provided written informed consent before completing self-report measures and performing the pre-training experimental tasks while EEG was recorded. Participants were then randomly assigned to two weeks of daily mindfulness or active control training (details below). Immediately after the last session of training, all participants completed their post-training testing session while EEG was recorded, followed by post-training self-report measures and debriefing. Each experimental session lasted ~3 h in duration and included other measures not reported in this paper.

Self-Report Measures

Demographic Information

All participants completed a basic demographic questionnaire that surveyed age, level of education and any previous meditation experience.

Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003)

This measure consists of 15 items designed to assess a core characteristic of dispositional or trait mindfulness. All participants completed the validated scale using a 1–6 Likert scale (*almost always* to *almost never*). The scale has a single-factor structure, resulting in a single total score. The final score is computed by calculating the mean responses of all 15 items. Higher scores indicate higher levels of trait mindfulness. Sample items include: “I do jobs or tasks automatically without being aware of what I am doing” and “I find myself doing things without paying attention” (both reverse scored).

Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006)

This measure consists of 39 items designed to assess five factors that represent elements of mindfulness as it is currently conceptualized. It contains items from the Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003), the Freiburg Mindfulness Inventory (FMI; Walach et al., 2006), the Kentucky Inventory of Mindfulness Skills (KIMS; Baer et al., 2004), the Cognitive and Affective Mindfulness Scale (CAMS; Feldman et al., 2007) and the mindfulness Questionnaire (MQ; Chadwick et al., 2005). Baer et al. (2006) conducted an exploratory factor analysis to identify five common subscales or facets of mindfulness: *Observing*, *Describing*, *Acting with Awareness*, *Nonjudging of inner experience*, and *Nonreactivity to inner experience*. *Observing* includes noticing or attending to internal and external experiences (such as sensations, cognitions, and emotions); *Describing* involves the ability to articulate internal experience with words; *Acting with Awareness* refers to the attention directed to observing one's activities in the present moment; *Nonjudging of Inner Experience* involves taking a non-evaluative stance towards thoughts and feelings; *Nonreactivity to Inner Experience* refers to disengaging from elaborative processing of thoughts or emotions that arise. Sample items include: "I notice the smells and aromas of things," (*Observing*); "I am good at finding words to describe my feelings," (*Describing*); "I find myself doing things without paying attention," (*Act with awareness*; reverse-scored); "I think some of my emotions are bad or inappropriate and I should not feel them," (*Nonjudging*; reverse-scored); and "I perceive my feelings and emotions without having to react to them," (*Nonreactivity*). All items are rated on a 1–5 Likert scale (*Never or very rarely true* to *Very often or always true*). The ratings are added across each subscale to produce a total for each facet (ranging from 8 to 40) as well as a grand total for all five facets (ranging from 39 to 195). Higher scores indicate higher levels of facet or total trait mindfulness.

Freiburg Mindfulness Inventory (FMI; Walach et al., 2006)

The FMI is a 14-item inventory designed to measure the experience of mindfulness. Participants rate statements such as "I am open to the experience of the present moment" on a four-point scale from 1 (rarely) to 4 (always). Scores range from 14 to 56 with higher scores indicating a higher degree of mindfulness. The FMI was used as a manipulation check to evaluate whether participants were engaged in a mindful state and whether this changed after training (Zeidan et al., 2010).

Mindfulness and Active Control Training Sessions

Both the mindfulness and active control training sessions consisted of daily 20-minute guided meditation sessions instructed by the same experienced instructor. Four of the sessions were held in group format, while the remaining sessions were completed independently using recorded video sessions. Each in-person group training session consisted of 2 to 10 people and was distributed evenly across the two-week program. To maintain consistency over the two weeks, the meditation instructor used the same mindfulness or active control script for both group and video training sessions. Consistent with formal mindfulness training procedures, in the mindfulness training sessions, participants were instructed to focus their attention internally on the sensations of their breath; observing distracting thoughts, feelings or sensations without judgment or elaboration; and re-directing attention back to their breath. The active control condition also presents guided training, however, attention is oriented externally to the narration of a nature walk, where elaboration of distracting thoughts, feelings or sensations is experienced with no explicit re-direction of attention to the narration or visualization. Critically, both conditions present a type of guided meditation, so that the specific training offered by mindfulness meditation can be effectively isolated.

Materials and Apparatus

All stimuli were presented on a Pentium class computer with Presentations® experimental control software (Neuro Behavioural Systems; version 14.3) on a 17-inch CRT monitor with a refresh rate of 85 Hz. The stimuli appeared in black, sans-serif numerals in the center of a grey background. Visual angle of the stimuli ranged from 5˚ to 6˚ horizontally between left and right edges of the outermost numbers and from 3˚ to 4˚ vertically between upper and lower edges of the outermost numbers. A chinrest was used to maintain a consistent viewing distance of approximately 80 cm between participants.

The Titrated Digit Stroop Task

The Digit Stroop task is a variation of the classic Stroop task, used to measure cognitive control and executive attention (Stroop, 1935). The task stimuli were strings of 1 to 6 digits presented in the center of a grey screen. All digits in the array had the same identity (1, 2, 3, 4, 5, or 6) and the number of digits presented varied randomly. The digits were mapped to computer keys along the bottom edge of the keyboard: “z x c” were used for left hand responses and represented digits 1, 2, 3, respectively, while “, . /” were used for right hand responses and represented digits 4, 5, 6, respectively. Participants were asked to respond as quickly and as accurately as possible by identifying the number of digits in the string, while ignoring the identity of the digits themselves. For example, the correct response to the stimulus, “5 5 5 5” is 4 (there are 4 digits) and is executed by pressing the “,” key. The stimulus set consisted of equal congruent and incongruent trials. On congruent trials, the string length was equivalent to the identity of the digit presented (e.g., the correct answer to “6 6 6 6 6 6” is ‘6’). On incongruent trials, the string length did not match the digit identity (e.g., the correct answer to “3 3” is “2”). In between trials, a fixation cross (+) was displayed at the center of the screen for an inter-trial interval (ITI) that varied randomly from 400 to 800 milliseconds. On each trial, the stimulus duration randomly varied from 800 to 1200 milliseconds and was titrated (+/- 20 ms) every 20 trials to maintain an accuracy level between 70% and 80%. For example, if mean accuracy exceeded 80% on the last 20 trials, the stimulus duration of the next 20 trials was decreased by 20 ms to increase difficulty. Similarly, if mean accuracy dropped below 70% on the last 20 trials, the stimulus duration of the following 20 trials was increased by 20 ms. If participants were too slow at responding to a stimulus (response time exceeded stimulus duration), a warning appeared on the screen that read, “Too Slow!!!”. In this way, task difficulty was maintained and participants were required to adjust the speed of response accordingly. The task consisted of 1080 trials in total (540 congruent, 540 incongruent), randomly presented in 20 blocks of 54 trials. To reduce blinking and general movement that might interfere with task-relevant ERPs, a message appeared after every 10 trials indicating that participants could take a “blink break”. Brief breaks were also provided between each experimental block. Participants resumed the experiment by pressing one of the response keys to start the next trial.

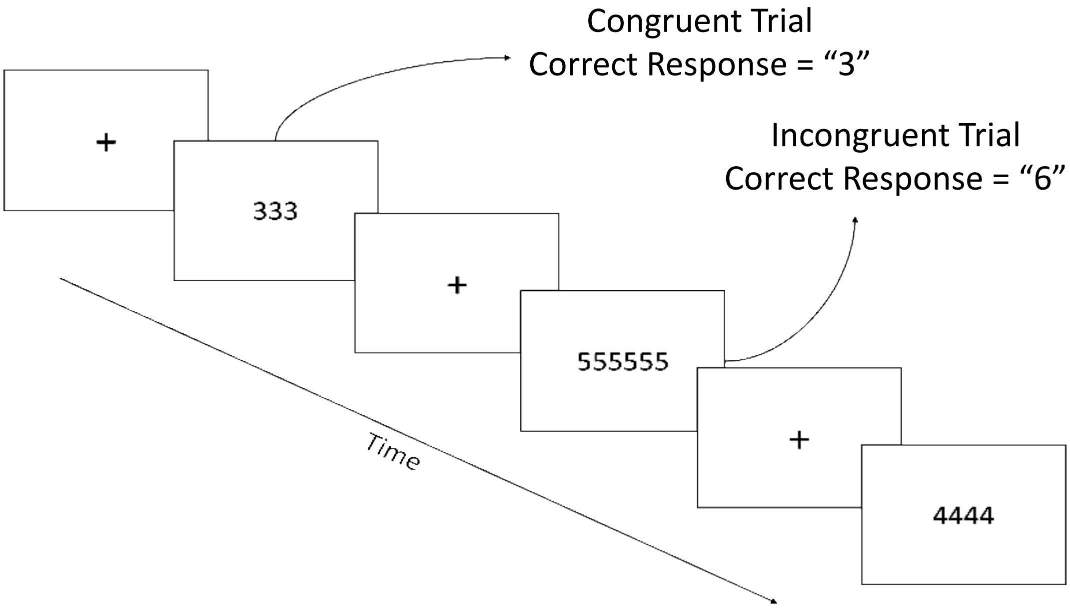

Figure 1. Illustration of congruent and incongruent trial types presented during the modified Digit Stroop Task. Inter-trial-interval (ITI) was randomized between 400 and 800 ms. Stimulus duration was randomized between 800 and 1200 ms at the beginning of the experiment and was titrated (+/– 20 ms) every 20 trials to maintain accuracy level between 70% and 80%. The task consisted of 1080 trials (50% congruent, 50% incongruent) randomly presented in 20 experimental blocks consisting of 54 trials.

Electrophysiological Recording

Continuous EEG activity was recorded from 128 Ag/AgCl scalp electrodes with a BioSemi Active-Two amplifier system (BioSemi, Amsterdam, Netherlands). Four electrooculogram (EOG) electrodes were placed at the outer canthi and just below each eye to monitor horizontal and vertical eye movements for removal of trials with eye artifacts. Two additional electrodes, a common mode sense (CMS) active electrode and a driven right leg (DRL) passive electrode were also used. These electrodes replace the “ground” electrodes used in conventional systems (www.biosemi.com/faq/cms&drl.htm). The continuous signal was acquired with an open passband from DC to 150 Hz and digitized at 512 Hz. The signal was bandpass filtered offline at 0.1 to 30 Hz using a Hamming windowed FIR filter and re-referenced to a common average reference. Bad channels were interpolated using the three nearest channels if the standard deviation of the channel exceeded 200mV before computing the average reference. Offline signal processing and averaging were done using EEGLAB version 13.5.4b (Delorme & Makeig, 2004) and ERPLAB version 5.0 (Lopez-Calderon & Luck, 2014). Infomax ICA algorithm (Bell & Sejnowski, 1995) was computed and artifactual independent components or epochs containing artifacts (e.g., muscle or eye movements) were removed manually after visual inspection. EEG was segmented, binned and epoched from -300ms prestimulus to 900ms post-stimulus. A pre-stimulus baseline correction from -300ms to -100ms was applied to avoid correcting anticipatory potentials like the ERN. Stimulus-locked and response-locked ERPs were averaged in the time domain for each stimulus category (congruent vs. incongruent), for each participant. Averaged waveforms for each participant were used to create grand averages for each group, before and after training.

Behavioural and ERP Data Analysis

Response times were measured by calculating mean RT for congruent trials, incongruent trials and total trials. Accuracy was measured by calculating proportion of correct trials out of correct, incorrect and miss trials. Therefore, congruent accuracy was measured by calculating proportion of correct congruent trials; incongruent accuracy was measured by calculating proportion of correct incongruent trials; and total accuracy was measured by calculating proportion of all correct trials. Post-error slowing (PES) was measured by calculating mean RT of correct trials following an error response. Congruent PES was measured by calculating mean RT on correct congruent trials following an error, incongruent PES was measured by calculating mean RT on correct incongruent trials following an error, and total PES was measured by calculating mean RT on all correct trials following an error. Finally, the Stroop interference effect was calculated by subtracting the mean RT on congruent trials from the mean RT on incongruent trials. This difference score was then used as a dependent variable in subsequent analyses.

Visual inspection of the ERP waveform across electrode sites and stimulus conditions revealed that the time windows for extraction of the mean amplitude, peak amplitude and peak latency for each ERP component. The P1 and N1 were best captured by small clusters of left parietal-occipital electrodes (PO7 and PO5) and right parietal-occipital electrodes (PO8 and PO6). Therefore, mean amplitude, peak amplitude and peak latency were extracted and averaged for left (PO7 and PO5) and right (PO8 and PO6) electrode clusters from a time window of 60 to 120 ms for the P1 component and a time window of 120 to 220 ms for the N1 component. The fronto-central N2 and P3a were best captured at electrode FCz by a time window of 250 to 350 ms and 325 to 425 ms, respectively. The P3b was on average ~250-450 ms after stimulus onset and was maximally represented at electrode site Pz. Therefore, mean amplitude was calculated using a time window of 250 to 450 ms, while peak amplitude and peak latency was extracted from a 200 to 500 ms time window to ensure peaks were captured during extraction. These time windows are consistent with previous literature examining the P3b during Stroop task performance (Moore et al., 2012; Malinowski et al., 2017). The ERN and Pe were best captured at the FCz electrode by a time window of –50 to 100 ms and 75 to 300 ms, respectively.

Results

Self-Report Measures

Independent samples t-tests were conducted to assess differences between baseline variables for the two training groups. At baseline, participants in the mindfulness and control groups did not differ on any of the included variables (all *p* values > .084). However, there was a significant difference on Levene's Test for Equality of Variances for baseline Observe scores (*F*

= 7.83, *p* = .008), which suggests unequal variances among groups. A Welch's t-test (for unequal variances) confirmed that the baseline Observe scores were not significantly different from one another [*t*(24.994) = .82, *p* = .375].

Repeated measures ANOVAs with *Group x Time* as factors were conducted for the MAAS, FFMQ, and the FMI to assess group differences across time of training (i.e., *Group x Time* interactions). There was no significant main effect of *Group*, *Tim*e, or significant *Group x Time* interactions for the MAAS, FFMQ Total, FFMQ Describe or FFMQ Acting with Awareness measures (all *p* values > .071). There was a main effect of *Time* for FFMQ-Observe [*F*(1,37) = 16.16, *p* < .001], FFMQ-Nonjudge [*F*(1,37) = 7.69, *p* = .009], and FFMQ-Nonreact [*F*(1,37) = 7.83, *p* = .008]. Both groups showed significant increase on the FFMQ-Observe and FFMQ-Nonreact facets, as well as a significant decrease on the FFMQ-Nonjudge facet after training. There was also a significant main effect of *Time* [*F*(1,37) = 14.57, *p* < .001] and a significant *Group x Time* interaction [*F*(1,36) = 4.28, *p* = .046] for the FMI scale. Post-hoc pairwise comparisons using the Bonferroni correction showed that FMI scores significantly increased for the mindfulness group after training (from 31.14 before to 36.19 after, mean difference of 5.05, *p* < .001) but did not significantly change for the control group (from 32.56 before to 34.06 after, mean difference of 1.50, *p* = .241). They also showed that the mindfulness and control group were not significantly different from each other before (*p* = .460) or after training (*p* = .304). Therefore, both the main effect of *Time* and the *Group x Time* interaction was driven by the significant increase of FMI scores after mindfulness training.

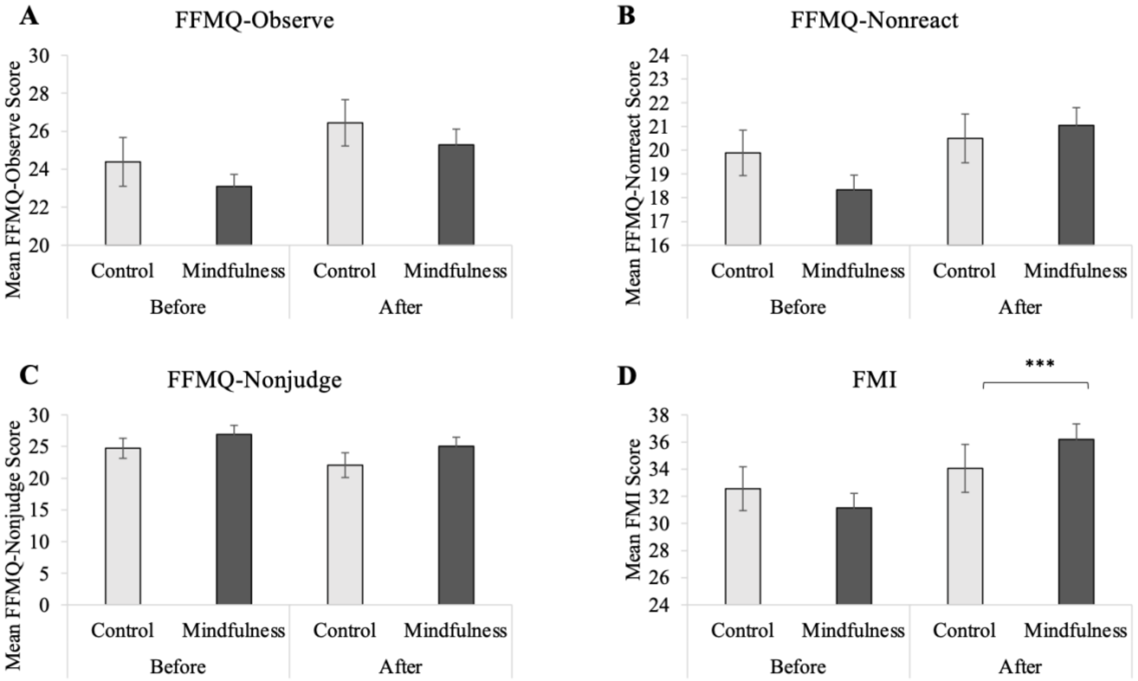

Figure 2. Mean scores for each group across time depicted for (**A**) the Observe subscale of the Five Facet Mindfulness Questionnaire (FFMQ), (**B**) the Nonjudge subscale of the FFMQ, (**C**) the Nonreact subscale of the FFMQ and (**D**) the Freiburg Mindfulness Inventory (FMI). Overall, FFMQ-Observe (**A**) and FFMQ-Nonreact (**C**) scores increased over time in both groups, while FFMQ-Nonjudge (**B**) scores decreased over time for both groups. Only the mindfulness group showed significant increase on the FMI after training (**D**). Error bars represent standard errors. ***p < .001

Behavioural Results

A series of 2 x 2 x 2 mixed repeated measures ANOVAs with *Group x Time x Congruency* as factors were conducted for response times (RTs), accuracy and Post Error Slowing (PES). 2 x 2 mixed repeated measures ANOVAs with *Group x Time* as factors were conducted for total RT, total accuracy, total PES and the Stroop interference effect. Post-hoc pairwise comparisons using the Bonferroni correction were conducted to interpret significant interactions. Independent samples t tests were also conducted to assess baseline differences between groups, which showed no significant difference at baseline between the mindfulness group and the control group.

Response Time (RT)

Group x Time x Congruency mixed repeated measures ANOVA revealed a significant main effect of *Congruency, F*(1,37) = 683.49, *p* < .001, a significant main effect of *Time*, F(1,37) = 216.74, *p* < .001, and a significant *Congruency x Time* interaction [*F*(1,37) = 78.98, *p* < .001], but no other significant main effect or interaction was observed (all *p* values > .153). Response times were significantly faster for congruent trials than incongruent trials (main effect of *Congruency*) and got significantly faster after training overall (main effect of *Time)*. Post hoc pairwise comparisons of the *Congruency x Time* interaction showed that RT significantly decreased for both congruent trials (from 542.75 ms to 503.55 ms, *p* < .001) and incongruent trials (from 598.43 ms to 544.26 ms, *p* < .001) but this mean difference was greater for incongruent trials (-54.17 ms) than congruent trials (-39.20 ms). The difference in RT between congruent and incongruent trials (Stroop interference effect) was also significantly different before training (*p* < .001) and after training (*p* < .001) regardless of group, as would be expected for a Stroop task, but this mean difference was greater before training (-55.67 ms) than after training (-40.70 ms). *Group x Time* repeated measures ANOVA for Total RT had no significant main effect of *Group*, *F*(1,37) = .62, *p* = .438, or significant *Group x Time* interaction, *F*(1,37) = .77, *p* = .386, but there was a significant main effect of *Time*, *F*(1, 37) = 206.39, *p* < .001, which showed the same pattern of decrease in RT after training. Overall, as expected, response times were faster for congruent trials than incongruent trials and were faster after training. The difference between congruency was also significant before and after training but got smaller after training.

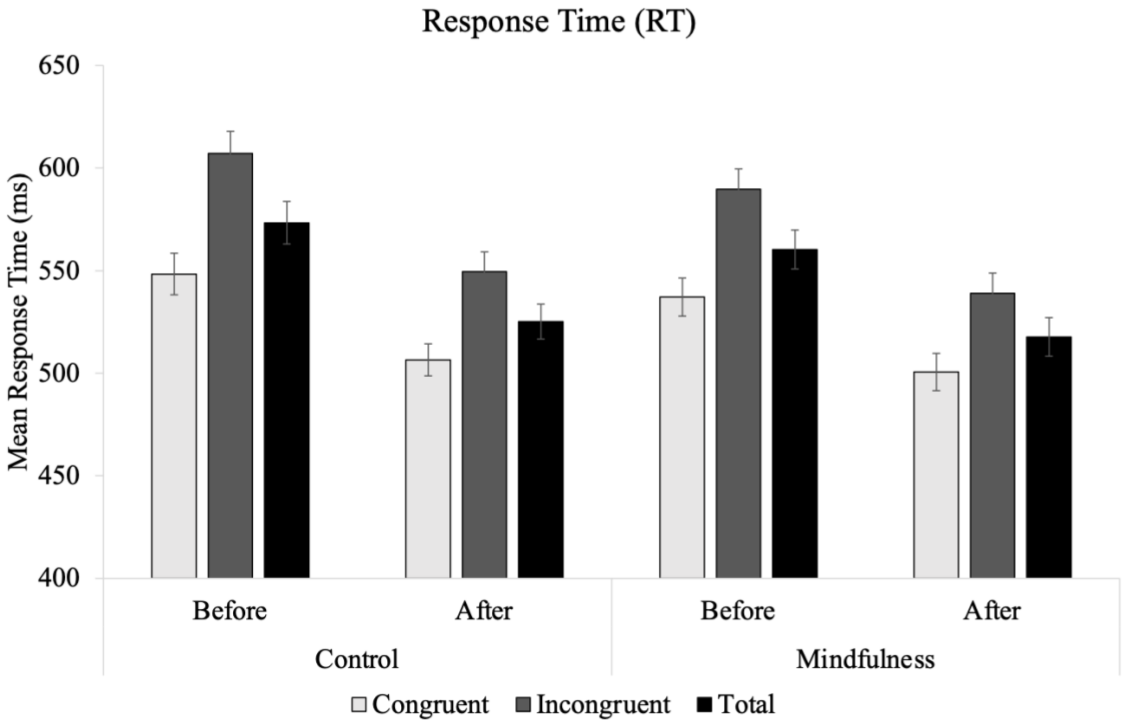

Figure 3. Mean response time (RT) in milliseconds (ms) for congruent trials, incongruent trials and total trials (collapsed across congruency) organized by group, before and after training. Overall, RTs on congruent trials are faster than RTs on incongruent trials, RTs decrease over time, the congruency difference between RTs decreases over time and this difference is greater for incongruent RTs than congruent RTs over time. Error bars represent standard errors.

Accuracy

Group x Time x Congruency repeated measures ANOVA showed a significant main effect of *Congruency*, $F(1,36) = 397.86$, $p < .001$, but no other significant effects were observed (all p values > .058). *Group x Time* repeated measures ANOVA for Total Accuracy also revealed no significant effects (all p values > .340). Overall, as expected in a Stroop task, accuracy was greater on congruent trials than incongruent trials.

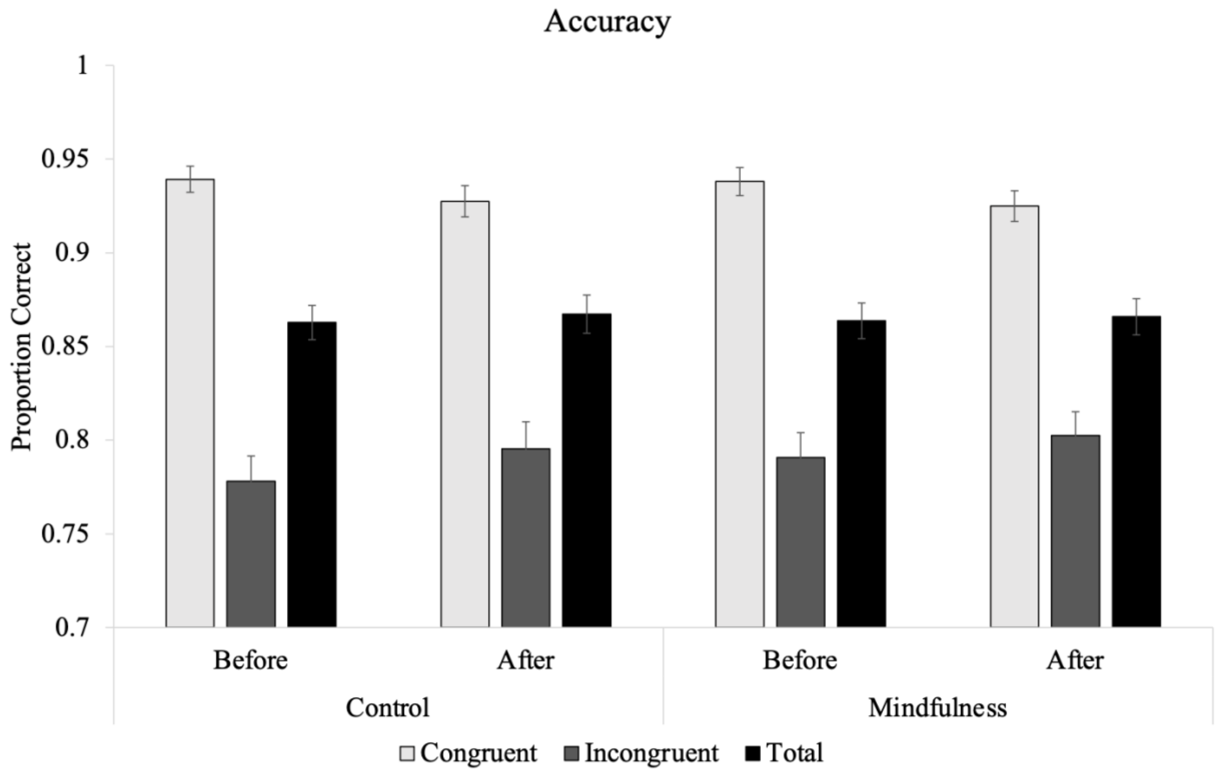

Figure 4. Accuracy depicted by proportion correct of congruent trials, incongruent trials and total trials organized by group, before and after training. Overall, accuracy was significantly greater on congruent trials than incongruent trials. Error bars represent standard errors.

Post-Error Slowing (PES)

Group x Time x Congruency repeated measures ANOVA showed a significant main effect of *Congruency*, $F(1, 37) = 289.87$, $p < .001$, significant main effect of *Time*, $F(1, 37) = 142.75$, $p < .001$, and significant *Congruency x Time* interaction, $F(1, 37) = 9.05$, $p = .005$. No other significant main effects or interactions were found (all other p values > .184). Post hoc pairwise comparisons using the Bonferroni correction showed that PES RT significantly decreased for both congruent trials (from 562.19 ms to 517.82 ms, $p < .001$) and incongruent trials (from 626.07 ms to 564.68 ms, $p < .001$) but this mean difference was greater for incongruent trials (-61.39 ms) than congruent trials (-44.37 ms). The difference in RT between congruent and incongruent trials (Stroop interference effect) was also significantly different before training ($p < .001$) and after training ($p < .001$) but this mean difference was greater before training (-63.89 ms) than after training (-46.86 ms). *Group x Time* repeated measures ANOVA for Total PES response times had a significant main effect of *Time*, $F(1, 37) = 128.62$, $p < .001$, but no significant main effect of *Group*, $F(1,37)= .32$, $p = .577$, or significant *Time x Group* interaction, $F(1, 37) = .02$, $p = .897$. As expected, post-error slowing for congruent trials, incongruent trials and total RT decreases after training (response time after an error gets faster after training) and is slower for incongruent trials than congruent trials overall, regardless of group. The difference in post-error slowing for congruent and incongruent trials is significant before and after training, but this difference gets smaller after training for both groups. Although both congruent and incongruent response times after an error get faster after training, this difference is greater for incongruent trials overall.

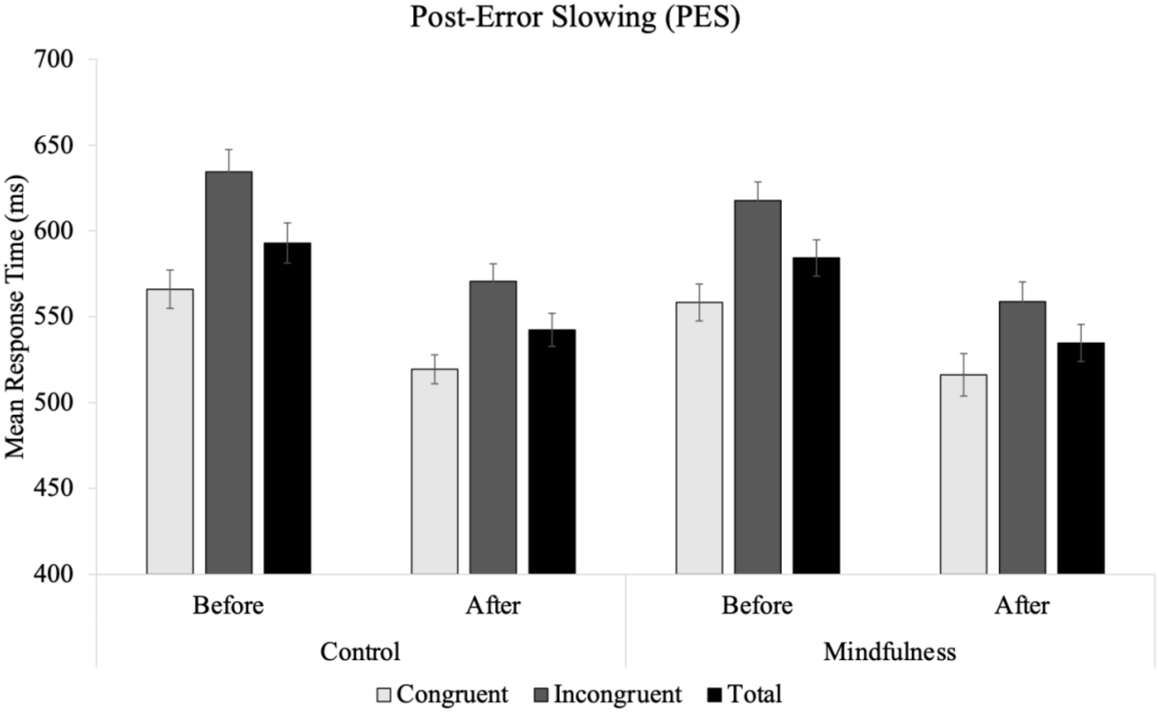

Figure 5. Mean response times (RT) in milliseconds (ms) for post-error slowing (PES) of congruent trials, incongruent trials and total trials organized by group, before and after training. Overall, PES was smaller on congruent trials than incongruent trials, and decreased after training for both groups. Error bars represent standard errors.

Stroop Interference Effect

Group x Time repeated measures ANOVA for Stroop effect showed no significant main effect of *Group*, *F*(1,37)= 2.13, *p* = .153, or significant *Time x Group* interaction, *F*(1, 37) = .21, *p* = .652, but there was a significant main effect of *Time*, *F*(1, 37) = 78.98, *p* < .001. Overall, the Stroop interference effect significantly decreased after training.

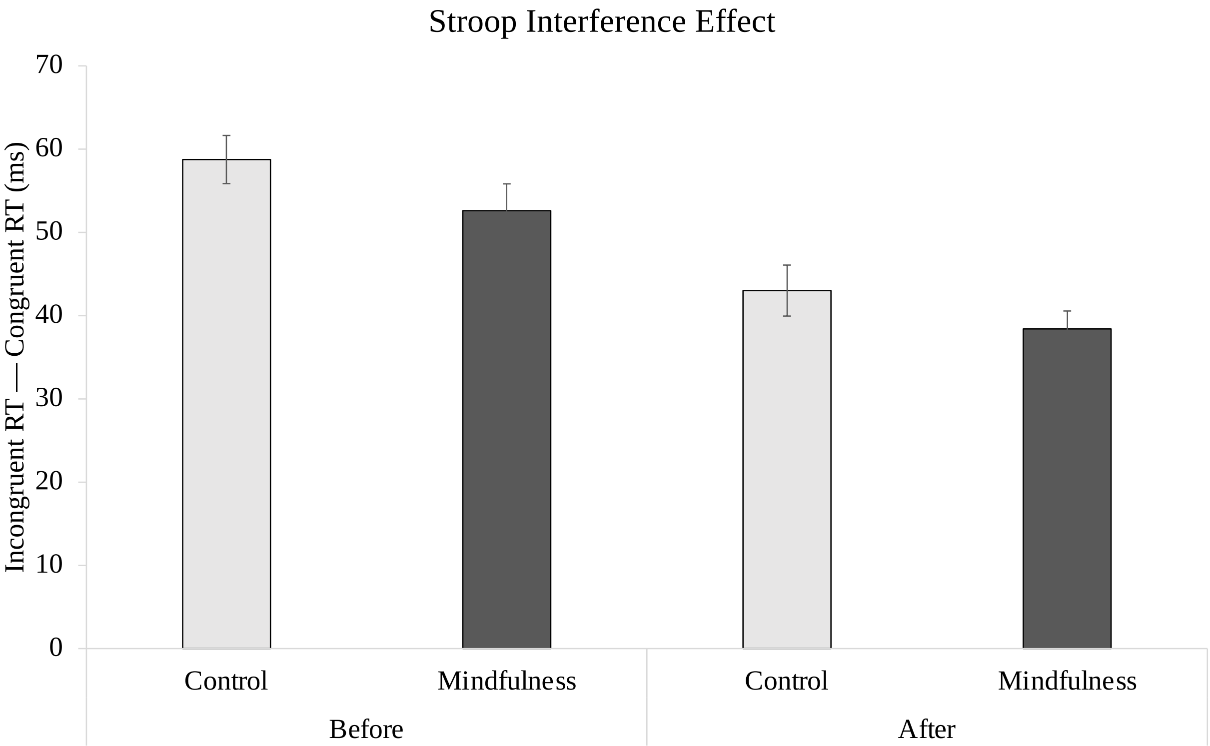

Figure 6. Mean response times (RT) in milliseconds (ms) for the Stroop interference effect (the difference between RT for congruent and incongruent trials) organized by group, before and after training. Overall, the Stroop interference effect was larger for the control group than the mindfulness group and decreases after training for both groups. Error bars represent standard errors.

ERP Results

A series of 2 x 2 x 2 mixed repeated measures ANOVAs with *Group x Time x Congruency* as factors were conducted to examine the role of each variable in the mean amplitudes, peak amplitudes and peak latencies of the P3b waveform at Pz electrode site, the N2, P3a, ERN, and Pe waveforms at FCz at the electrode site and maxima of the bilateral P1 and N1, which were best captured by small clusters of left parietal-occipital electrodes (PO7 and PO5) and right parietal-occiptal electrodes (PO8 and PO6).

P1 at PO7/PO5 and PO8/PO6 (60 to 120 ms)

The left and right P1 waveforms at the PO7/PO5 cluster and the PO8/PO6 cluster are depicted in Figure 7. *Group x Time x Congruency* ANOVAs revealed a significant main effect of *Group* for the left P1 peak latency [$F(1,37) = 4.94$, $p = .032$] and the right P1 peak latency [$F(1,37) = 7.29$, $p = .010$]. Overall, P1 peak latencies were earlier for the mindfulness group than the control group on both the left side (mindfulness left: 90.77 ms, control left: 98.12 ms) and the right side (mindfulness right: 86.40 ms, control right: 95.03 ms). There were also significant *Time x Group* interactions observed for the right P1 mean amplitude [$F(1,37) = 5.40$, $p = .026$] and peak amplitude [$F(1,37) = 7.95$, $p = .008$]. Post-hoc pairwise comparisons were conducted to interpret the *Time x Group* interactions for mean and peak amplitude. Although there were no significant comparisons for the right P1 mean amplitude *Time x Group* interaction (all p values > .092), post-hoc pairwise comparisons for the right P1 peak amplitude *Time x Group* interaction showed that the amplitude was significantly larger for the mindfulness group after training [mindfulness before = 4.49 μV, mindfulness after = 5.02 μV, $p = .014$], suggesting enhanced sensory processing sensitive to selective attention after mindfulness training. This difference did not exist in the control group (control before = 5.12 μV, control after = 4.79 μV, $p = .151$) or between groups before ($p = .507$) or after training ($p = .818$). No other significant effects were observed for the P1 waveform on the left or right side (all p values > .094 and .086 respectively).

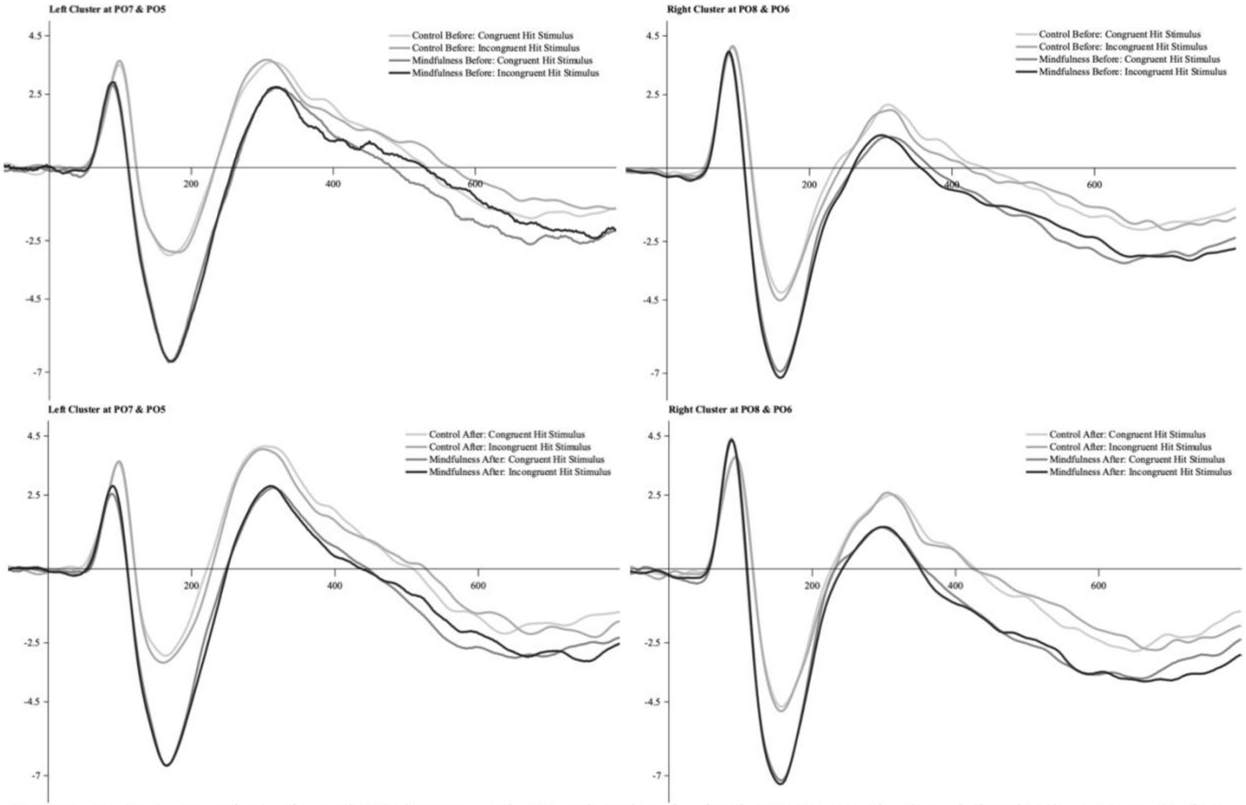

Figure 7. Top panel: Left and Right P1 and N1 stimulus-locked ERPs are depicted for both groups before training. Bottom panel: Left and Right P1 and N1 stimulus-locked ERPs are depicted for both groups after training. Left clusters: PO7 & PO5. Right clusters: PO8 & PO6. P1 latency window: 60–120ms, N1 latency window: 120–220ms.

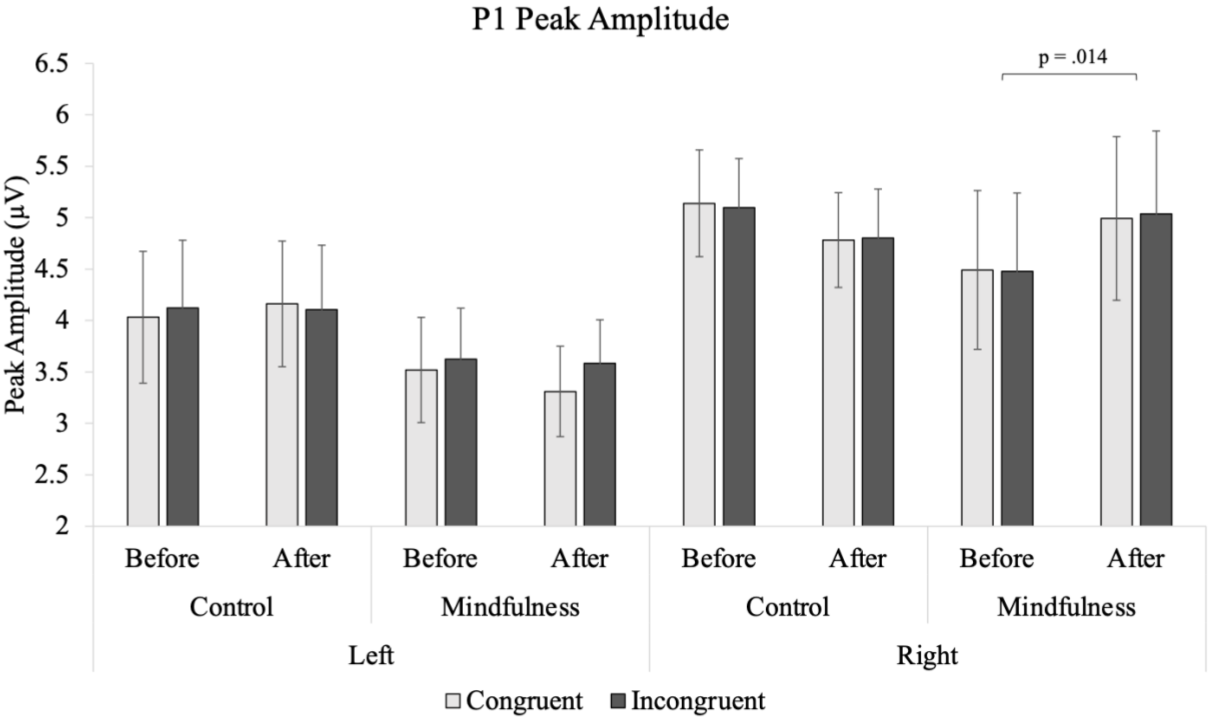

Figure 8. P1 peak amplitudes in microvolts (μV) for congruent and incongruent trials organized by group and hemisphere (left electrode clusters: PO7, PO5; right electrode clusters: PO8, PO6). Overall, there was a significant Time by Group interaction in the right hemisphere. Post-hoc pairwise comparisons revealed a significant increase in the right P1 peak amplitude for the mindfulness group after training (p = .014). Error bars represent standard errors.

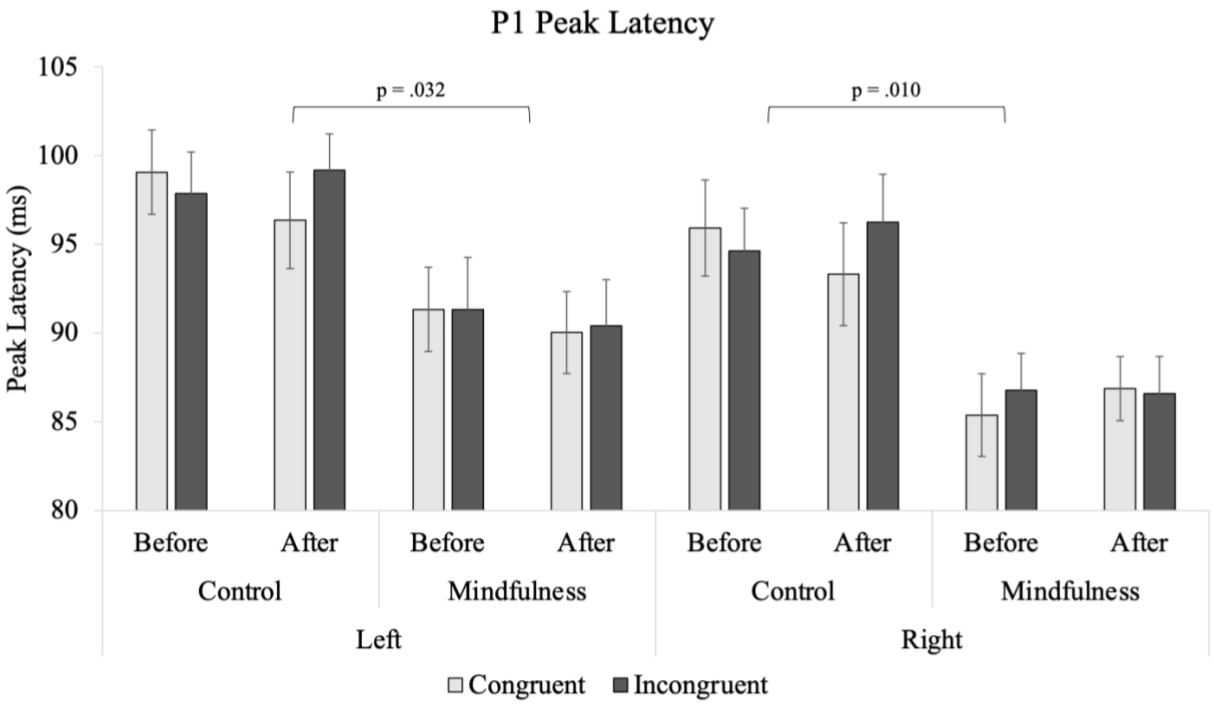

Figure 9. P1 peak latencies in milliseconds (ms) for congruent and incongruent trials organized by group and hemisphere (left electrode clusters: PO7, PO5; right electrode clusters: PO8, PO6). Overall, the mindfulness group had a significantly earlier P1 peak latency compared to the control group in both hemispheres (left P1 peak latency: p = .032, right P1 peak latency: p = .010). Error bars represent standard errors.

N1 at PO7/PO5 and PO8/PO6 (120 to 220 ms)

The left and right N1 waveforms at the PO7/PO5 cluster and the PO8/PO6 cluster are depicted in Figure 7. *Group x Time x Congruency* ANOVAs revealed the same pattern of effects for the left and right N1 mean and peak amplitudes. There was a significant main effect of *Congruency* for the left N1 mean amplitude [$F(1,37) = 8.72$, $p = .005$] and peak amplitude [$F(1,37) = 10.44$, $p = .003$] as well as the right N1 mean amplitude [$F(1,37) = 10.45$, $p = .003$] and peak amplitude [$F(1,37) = 14.70$, $p < .001$]. There was also a significant main effect of *Group* for the left N1 mean amplitude [$F(1,37) = 13.01$, $p < .001$] and peak amplitude [$F(1,37) = 8.69$, $p < .006$], as well the right N1 mean amplitude [$F(1,37) = 5.47$, $p < .025$] and peak amplitude [$F(1,37) = 4.27$, $p < .046$], suggesting group differences in sensory processing. Overall, the N1 mean and peak amplitudes were larger for the incongruent than congruent trials and larger for the mindfulness group than the control group in both hemispheres. This suggests greater sensory processing of incongruent trials relative to congruent trials and that overall, this sensory processing was greater for the mindfulness group in both hemispheres before and after training. There were no significant effects for the left N1 peak latency (all *p* values > .131), but there was a significant main effect of *Time* for the right N1 peak latency [*F*(1,37) = 7.20, *p* = .011]. Overall, the right N1 peak latency was significantly faster after training (before = 160.01 ms, after = 156.89 ms, *p* = .011). There were no other significant effects observed for the N1 waveform in the left or right cluster (all *p* values > .148 and .193, respectively).

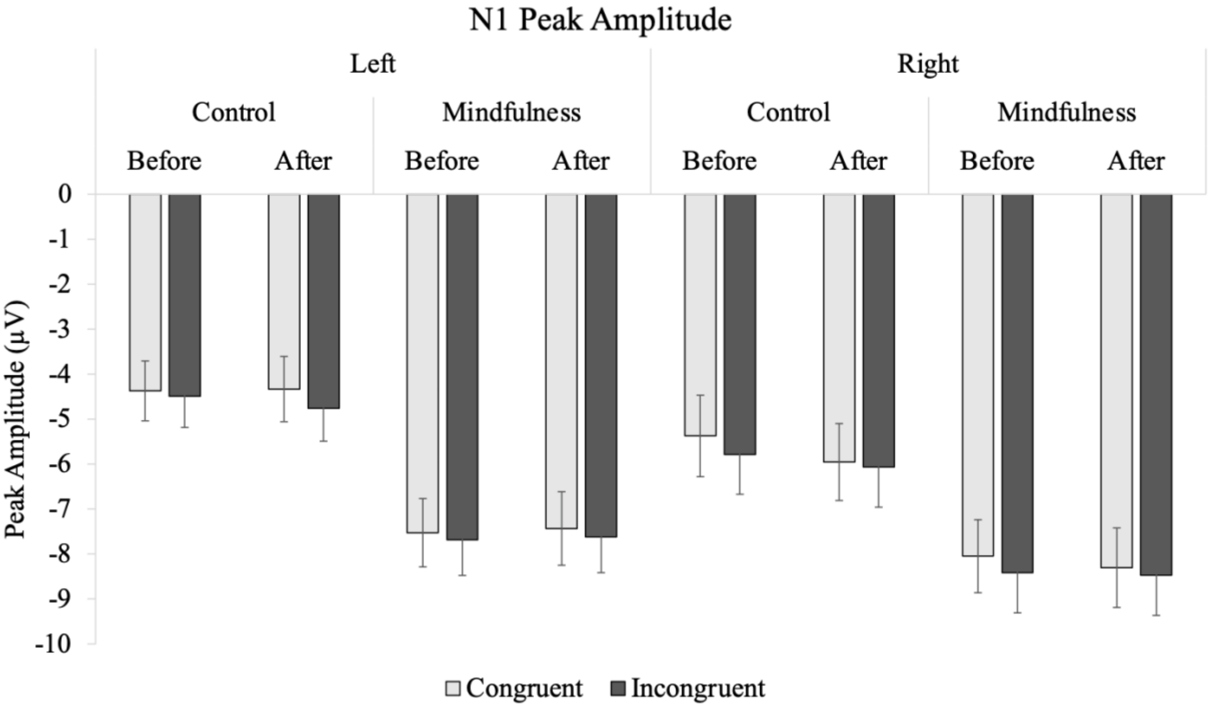

Figure 10. N1 peak amplitudes in microvolts (μV) for congruent and incongruent trials organized by group and hemisphere (left electrode clusters: PO7, PO5; right electrode clusters: PO8, PO6). Overall, N1 peak amplitudes were larger for incongruent trials than congruent trials in both hemispheres. The N1 peak amplitude was also larger for the mindfulness group compared to the control group in both hemispheres. Error bars represent standard errors.

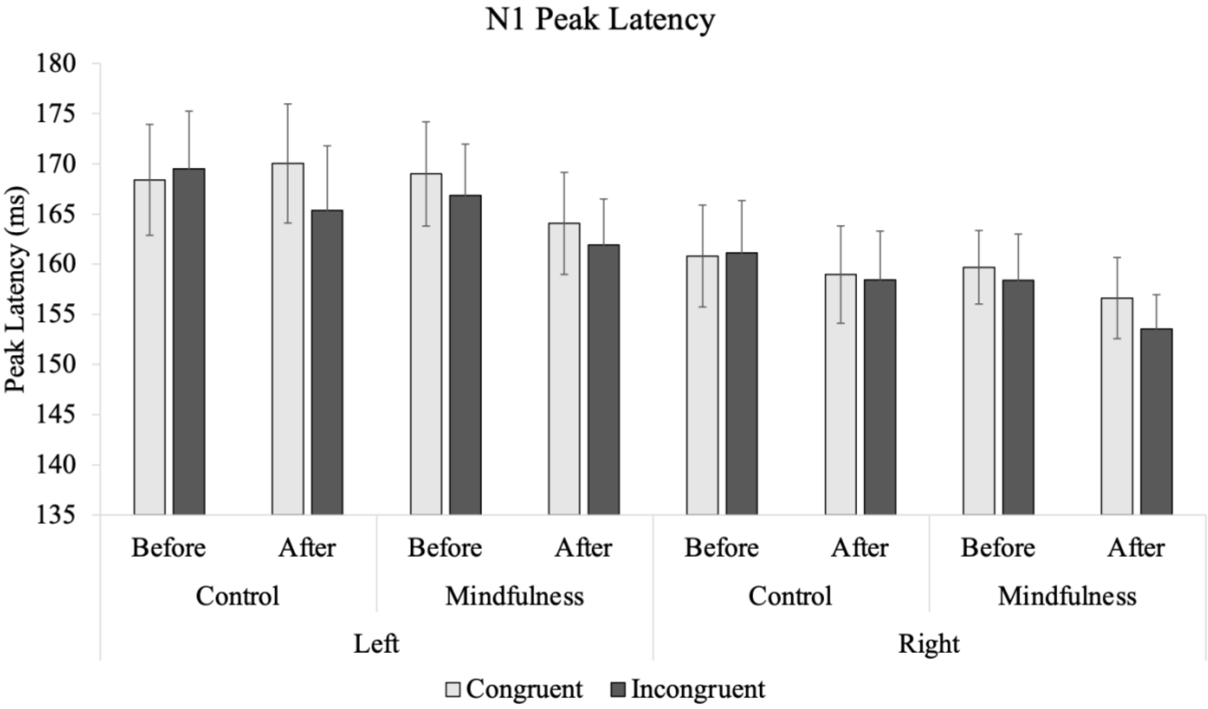

Figure 11. N1 peak latencies in milliseconds (ms) for congruent and incongruent trials organized by group and hemisphere (left electrode clusters: PO7, PO5; right electrode clusters: PO8, PO6). Overall, the both groups had a significantly earlier N1 peak latency in the right hemisphere after training. Error bars represent standard errors.

N2 at FCz (250 to 350 ms)

The N2 waveform at the FCz electrode site is depicted in Figure 12. Mixed repeated measures ANOVAs revealed significant effects for the mean amplitude, peak amplitude and the peak latency within a time window of 250 to 350 ms. There was a significant main effect of *Congruency* for the mean amplitude [$F(1,37) = 17.73$, $p < .001$] and the peak amplitude [$F(1,37) = 9.19$, $p = .004$], which showed that overall N2 mean and peak amplitudes were larger for incongruent trials (incongruent mean amplitude: –1.11 μV, incongruent peak amplitude: –2.18 μV) than congruent trials (congruent mean amplitude: –.77 μV, congruent peak amplitude: –1.90 μV), suggesting greater detection, monitoring or inhibition of conflict on incongruent trials relative to congruent trials. There was also a significant main effect of *Time* for the mean amplitude [$F(1,37) = 11.69$, $p = .002$], peak amplitude [$F(1,37) = 11.11$, $p = .002$] and peak latency [$F(1,37) = 9.19$, $p = .004$], which showed that after training the N2 waveform had a larger mean amplitude (before: –.65 μV, after: –1.23 μV) and peak amplitude (before: –1.70 μV, after: –2.38 μV), as well as an earlier peak latency (before: 297.08 ms, after: 291.23 ms). This suggests that after training, both groups showed greater conflict detection, monitoring or inhibition of incongruent trials and were faster at processing conflict, regardless of congruency. No other significant effects for the N2 mean amplitude, peak amplitude or peak latency were observed (all *p* values > .067).

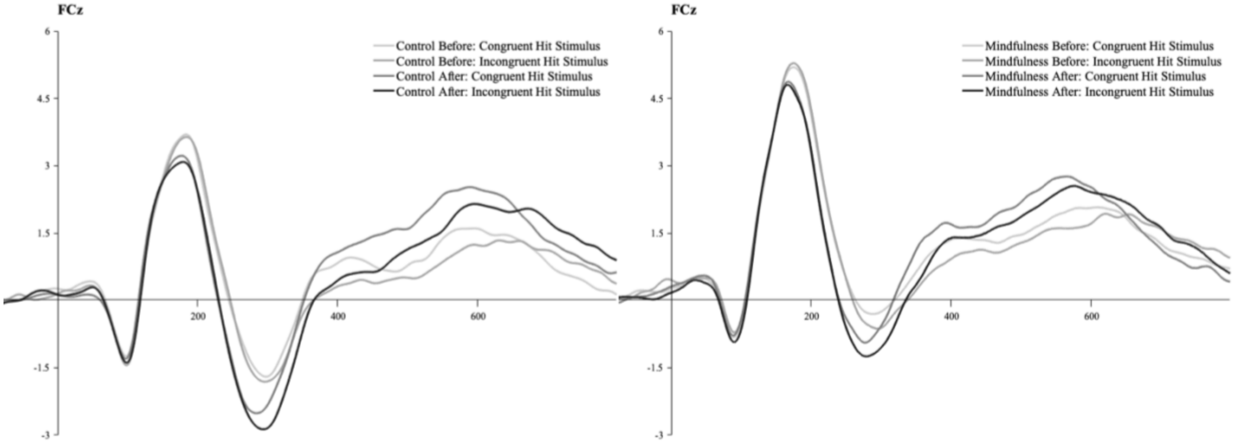

Figure 12. N2 and P3a ERPs are depicted at FCz for the control group before and after (left panel) and the mindfulness group before and after (right panel). Overall, N2 mean and peak amplitudes were larger for incongruent trials than congruent trials and larger after training for both groups. N2 peak latencies were also significantly faster after training in both groups. P3a amplitudes were larger for congruent trials than incongruent trials. Post-hoc pairwise comparisons of a significant Time x Group interaction for the P3a latency also showed that after training, P3a peak latencies were significantly slower for the control group compared to baseline ($p = .045$) and compared to the mindfulness group ($p = .017$). No significant differences were observed in the mindfulness group after training.

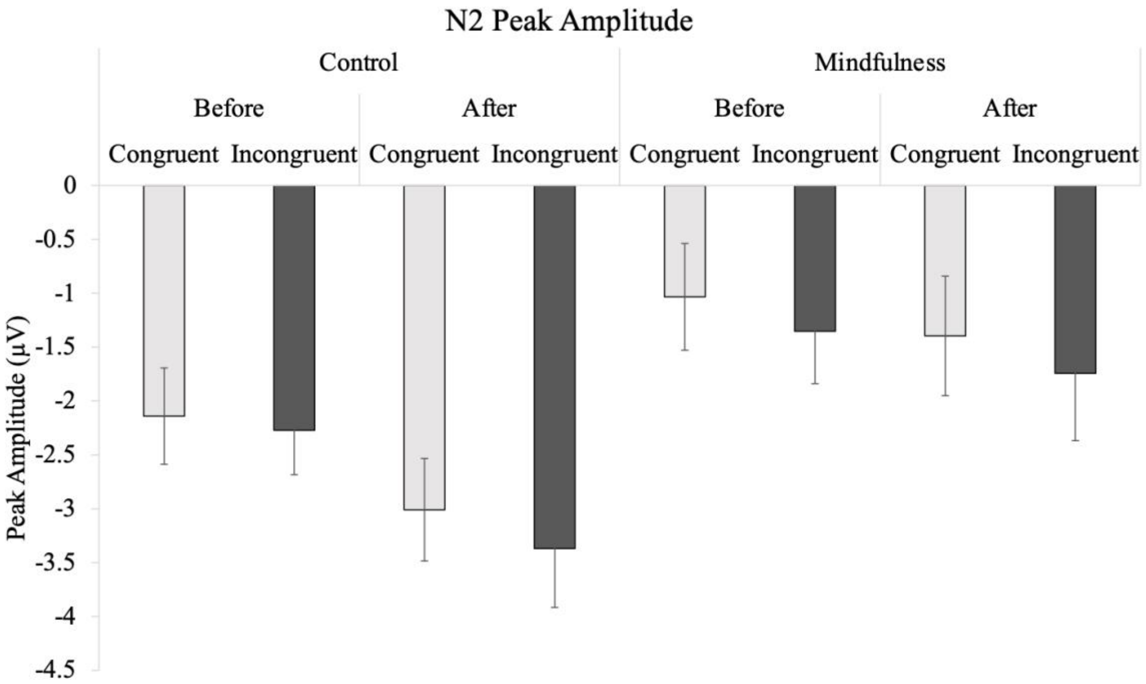

Figure 13. N2 peak amplitudes in microvolts (μV) for congruent and incongruent trials organized by group, before and after training. Overall, N2 peak amplitudes were larger for incongruent trials than congruent trials. N2 peak amplitude were also larger after training for both groups. N2 mean amplitudes showed the same pattern of results. Error bars represent standard errors.

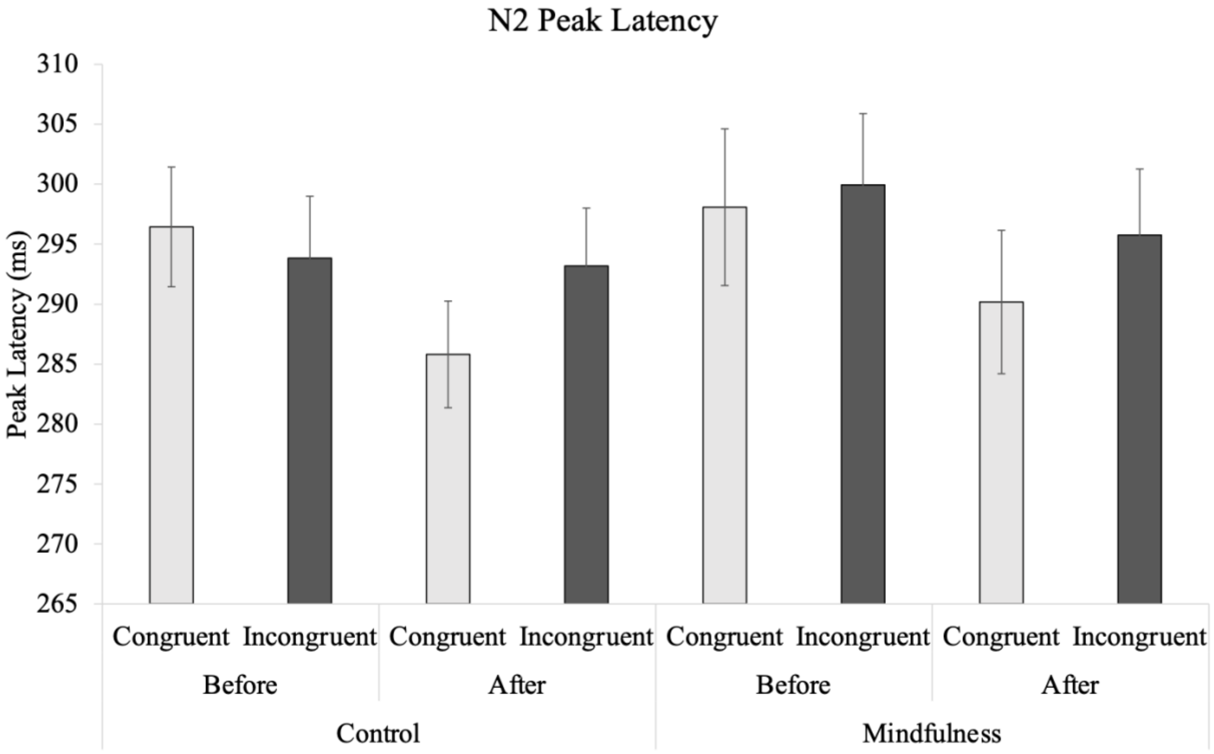

Figure 14. N2 peak latencies in milliseconds (ms) for congruent and incongruent trials organized by group, before and after training. Overall, N2 peak latencies were significantly faster after training in both groups. Error bars represent standard errors.

P3a at FCz (325 to 425 ms)

The P3a waveform at the FCz electrode site is depicted in Figure 12. Mixed repeated measures ANOVAs revealed significant effects for the mean amplitude, peak amplitude and peak latency within a time window of 325 to 425 ms. There was a significant main effect of *Congruency* for the P3a mean amplitude [$F(1,37) = 24.31$, $p < .001$] and peak amplitude [$F(1,37) = 21.21$, $p < .001$], where amplitudes were significantly larger for congruent (congruent mean amplitude: .78 μV, congruent peak amplitude: 1.68 μV) than incongruent trials (incongruent mean amplitude: .29 μV, incongruent peak amplitude: 1.11 μV). There was also a significant *Time x Group* cross-over interaction [$F(1,37) = 6.47$, $p = .015$] and a significant *Time x Congruency* cross-over interaction [$F(1,37) = 5.818$, $p = .021$] for the P3a peak latency. Post-hoc pairwise comparisons of the *Time x Group* interaction showed that the P3a peak latency for the control group was significantly later after training (control before = 389.54 ms, control after = 401.26 ms, *p* = .045), while there was no change in the mindfulness group (mindfulness before = 391.83 ms, mindfulness after = 383.93 ms, *p* = .140), suggesting a resistance to automatic or involuntary stimulus-driven attentional capture after mindfulness training. After training, this delayed P3a peak latency for the control group was significantly later than the mindfulness group (control after = 401.26 ms, mindfulness after = 383.93 ms, *p* = .017). Post-hoc pairwise comparisons of the *Time x Congruency* interaction were not significant, however, the cross-over interaction showed that P3a peak latency differs by congruency across time. Before training, the peak latency for congruent trials was later than the peak latency for incongruent trials, but after training, the peak latency for congruent trials was earlier than the peak latency for incongruent trials (congruent before = 392.80 ms, incongruent before = 388.57 ms, *p* = .416; congruent after = 389.55 ms, incongruent after = 395.64 ms, *p* = .142). There were no other significant effects observed for the P3a component (all *p* values > .161).

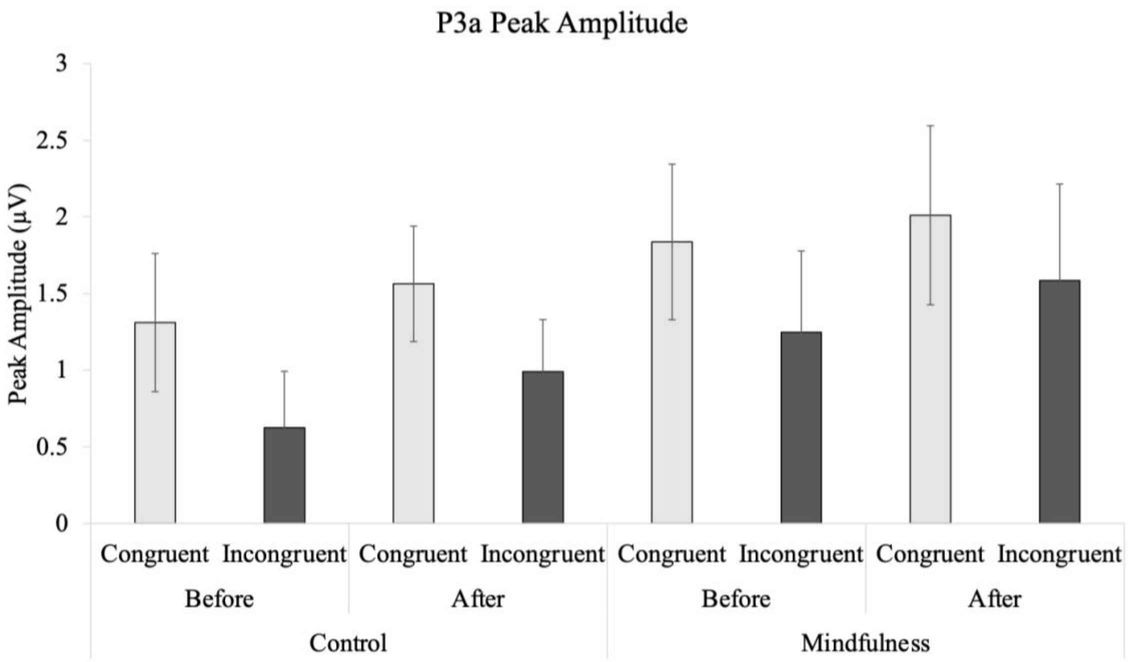

Figure 15. P3a peak amplitudes in microvolts (μV) for congruent and incongruent trials organized by group, before and after training. Overall, P3a amplitudes were larger for congruent trials than incongruent trials. Error bars represent standard errors.

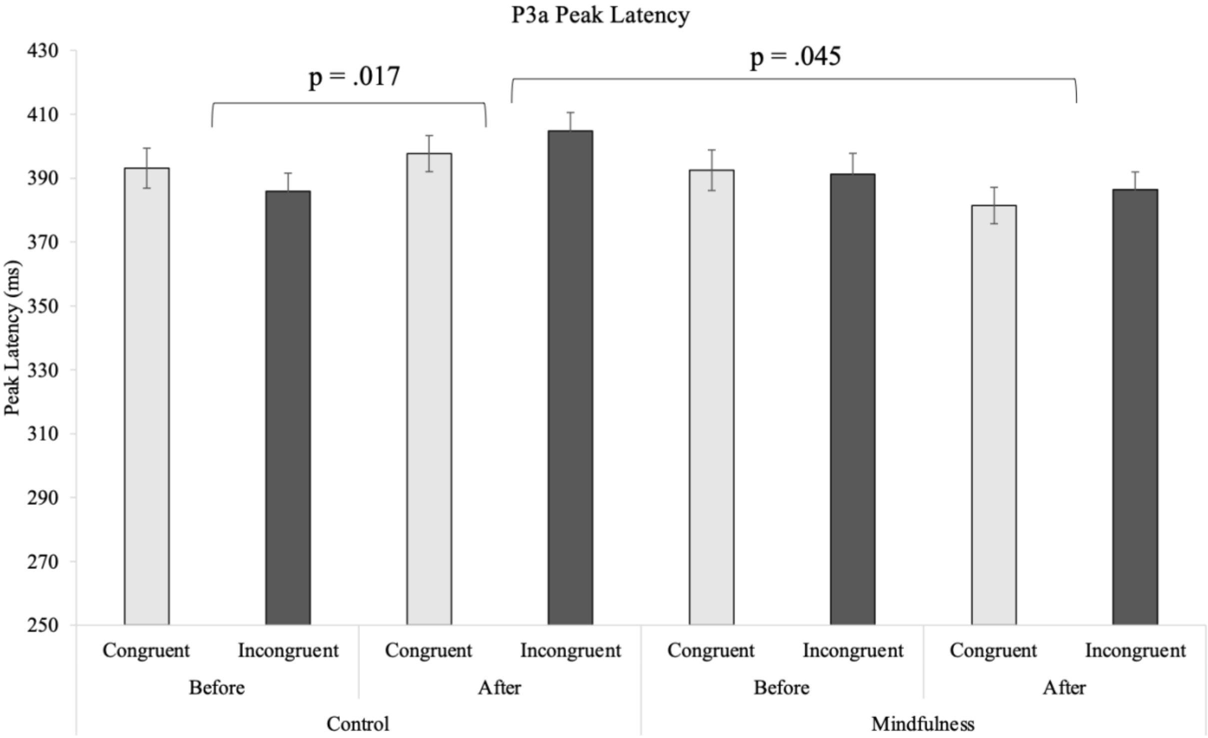

Figure 16. P3a peak latencies in milliseconds (ms) for congruent and incongruent trials organized by group, before and after training. Overall, there was a significant Time by Group interaction. Post-hoc pairwise comparisons showed that after training, P3a peak latencies were significantly slower for the control group compared to baseline (p = .045) and compared to the mindfulness group (p = .017). No significant differences were observed in the mindfulness group after training. Error bars represent standard errors.

P3b at Pz (250 to 550 ms)

The P3b waveform at the Pz electrode site is depicted in Figure 17. Mixed repeated measures ANOVAs revealed significant effects for the P3b mean amplitude, peak amplitude and peak latency within a time window of 250 to 350 ms. There was a significant main effect of *Congruency* for the mean amplitude [$F(1,37) = 8.79$, $p = .005$] and the peak amplitude [$F(1,37) = 13.74$, $p < .001$], where amplitudes were significantly larger for congruent than incongruent trials (congruent mean amplitude: 4.32 μV, incongruent mean amplitude: 4.05 μV, $p = .005$; congruent peak amplitude: 6.23 μV, incongruent peak amplitude: 5.77 μV, $p < .001$). There was also a significant *Time x Group* interaction for the P3b peak latency [$F(1,37) = 4.36$, $p = .044$]. Post-hoc pairwise analysis showed that the P3 peak occurred significantly earlier for the mindfulness group after training (latency before = 428.80 ms, latency after = 403.00 ms, *p* = .029), but this difference did not exist for the control group (latency before = 395.02 ms, latency after = 404.19 ms, *p* = .460), suggesting faster conscious evaluations of all stimuli after mindfulness training. Both groups were not significantly different from one another before (*p* = .087) or after training (*p* = .955). There were no other significant effects observed for the P3b component (all *p* values > .092).

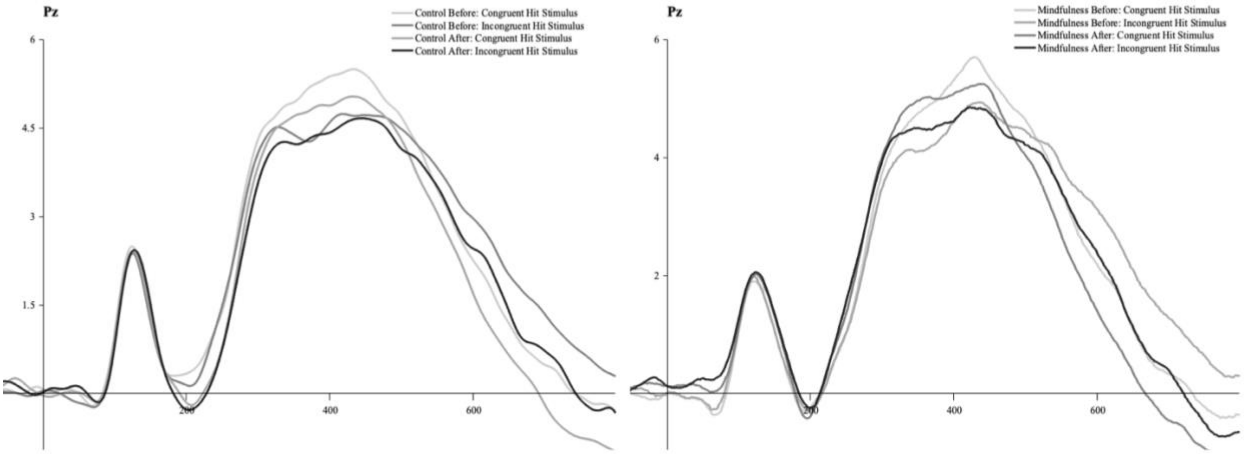

Figure 17. P3b ERPs are depicted at Pz with a time latency window of 250 to 550 ms for control group before and after (left panel) and mindfulness group before and after (right panel). Overall, P3b mean and peak amplitudes were larger for congruent trials than incongruent trials. Post-hoc pairwise comparisons of a significant Time by Group interaction showed that P3b peak latencies were significantly earlier in the mindfulness group after training (p = .029).

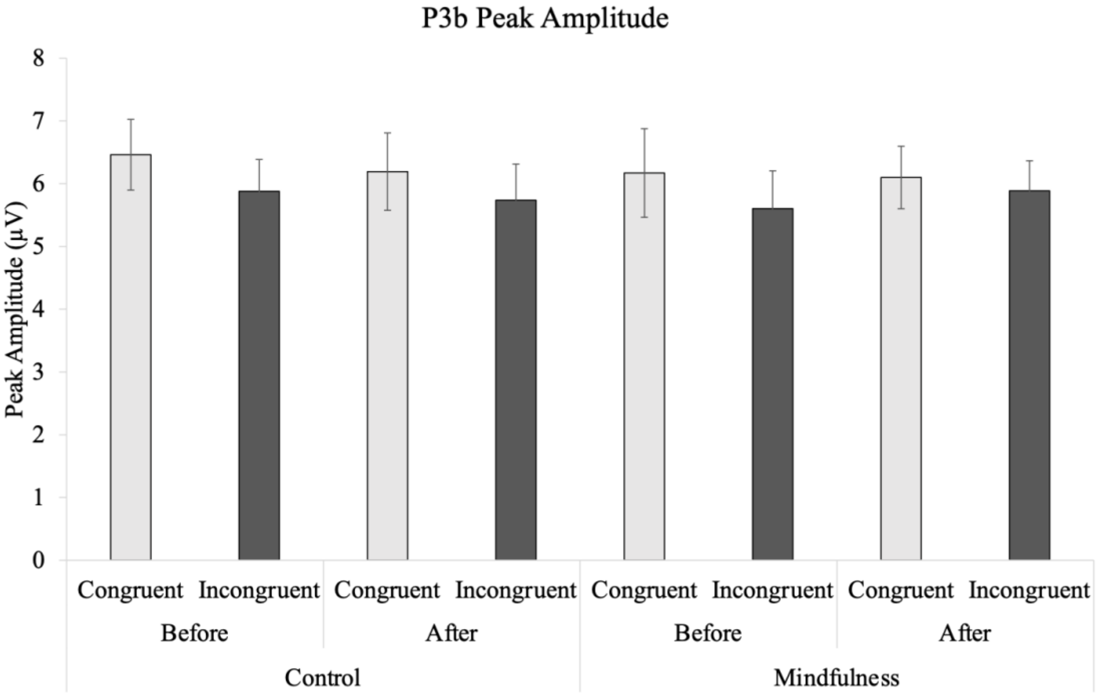

Figure 18. P3b peak amplitudes in microvolts (μV) for congruent and incongruent trials organized by group, before and after training. Overall, P3b peak amplitudes were larger for congruent trials than incongruent trials. P3b mean amplitudes showed the same pattern of results. Error bars represent standard errors.

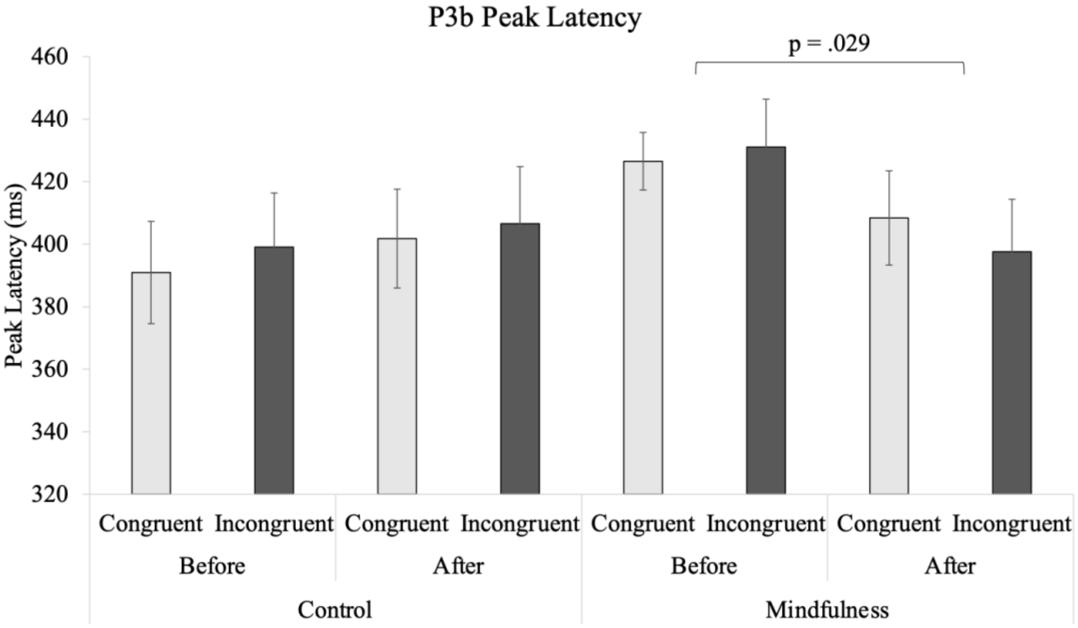

Figure 19. P3b peak latencies in milliseconds (ms) for congruent and incongruent trials organized by group, before and after training. Overall, P3b peak latencies were significantly earlier in the mindfulness group after training (p = .029). Error bars represent standard errors.

ERN at FCz (0 to 75 ms)

The ERN waveform at the FCz electrode site is depicted in Figure 20. Mixed repeated measures ANOVAs revealed significant effects for the mean amplitude and peak amplitude within a time window of 0 to 75 ms. There was a significant main effect of *Congruency* for the ERN mean amplitude [$F(1,37) = 4.28$, $p = .046$] and the peak amplitude [$F(1,37) = 10.00$, $p = .003$], where ERN amplitudes where significantly larger for congruent (congruent mean amplitude: –2.24 μV, congruent peak amplitude: –3.84 μV) than incongruent trials (incongruent mean amplitude: –1.84 μV, incongruent peak amplitude: –3.07 μV). This suggests that both groups showed greater reactivity to having made an error on the easier, congruent trials. There were no significant effects for the ERN peak latency (all p values > .271). There were also no other significant effects for the ERN waveform (all p values > .113).

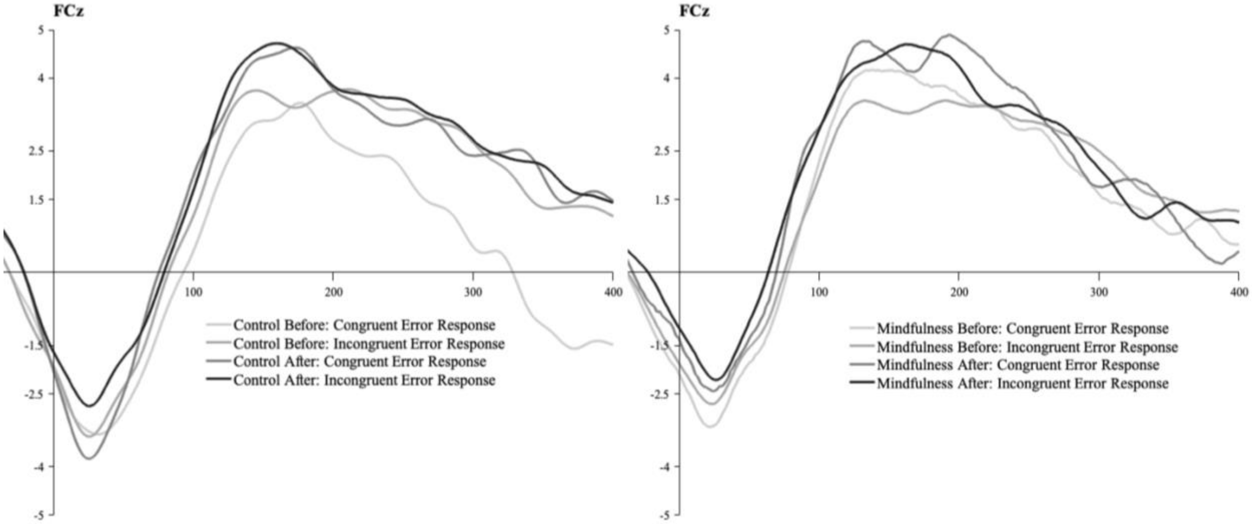

Figure 20. The error-related negativity (ERN) and error positivity (Pe) are depicted at FCz for the control group before and after (left panel) and the mindfulness group before and after (right panel). Overall, ERN mean and peak amplitudes were significantly larger for congruent errors than incongruent errors. There were no significant effects observed in the ERN peak latency between groups across time. Pe peak amplitudes were also significantly larger for congruent errors than incongruent errors and increased after training in both groups. Pe peak latencies were also significantly slower for congruent errors than incongruent errors.

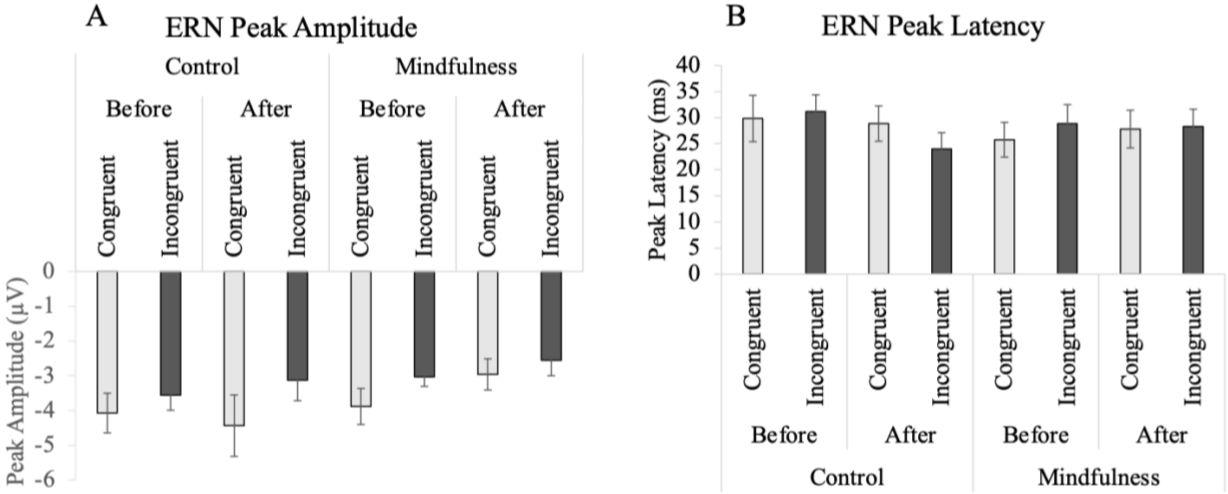

Figure 21. A) ERN peak amplitudes in microvolts (μV) for congruent and incongruent trials organized by group, before and after training and B) ERN peak latencies in milliseconds (ms) for congruent and incongruent trials organized by group, before and after training. Overall, ERN peak amplitudes were significantly larger for congruent errors than incongruent errors. ERN mean amplitudes showed the same pattern of results. There were no significant effects observed in the ERN peak latency between groups across time. Error bars represent standard errors.

Pe at FCz (100 to 200 ms)

The Pe waveform at the FCz electrode site is depicted in Figure 20. Mixed repeated measures ANOVAs revealed significant effects for the mean amplitude, peak amplitude and peak latency within a time window of 100 to 200 ms. There was a significant main effect of *Time* for the Pe mean amplitude [$F(1,37) = 4.73$, $p = .036$] and peak amplitude [$F(1,37) = 4.36$, $p = .044$], where the Pe was larger after training (mean amplitude after: 4.11 μV, peak amplitude after: 5.643 μV) compared to baseline (mean amplitude before: 3.22 μV, peak amplitude before: 4.72 μV). There was also a significant main effect of *Congruency* for the peak amplitude [$F(1,37) = 5.00$, $p = .031$] and peak latency [$F(1,37) = 4.55$, $p = .040$], where the Pe amplitude was larger for congruent (congruent peak amplitude: 5.56 μV) than incongruent trials (incongruent peak amplitude: 4.80 μV), but peaked earlier for incongruent (151.94 ms) than congruent trials (158.90 ms). This suggests that both groups were consciously processing and equally more aware of committing more salient errors on the “easier” congruent errors compared to incongruent errors and deferred or prolonged conscious processing of congruent errors relative to incongruent errors. There were no other significant effects observed for the Pe waveform (all *p* values > .120).

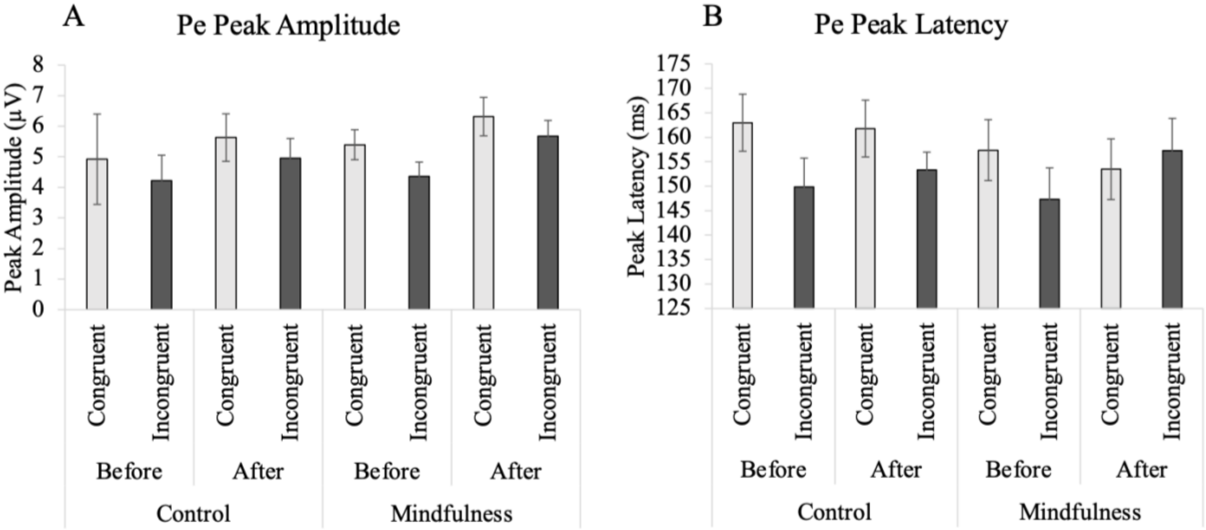

Figure 22. A) Pe peak amplitudes in microvolts (μV) for congruent and incongruent trials organized by group, before and after training and B) Pe peak latencies in milliseconds (ms) for congruent and incongruent trials organized by group, before and after training. Overall, Pe peak amplitudes were significantly larger for congruent errors than incongruent errors and increased after training in both groups. Pe peak latencies were also significantly slower for congruent errors than incongruent errors. Error bars represent standard errors.

Discussion

The current study attempts to address the inconsistencies outlined in the literature by comparing stimulus-locked and response-locked ERPs in a mindfulness training group and a novel active control training group using a cognitive control task designed to increase difficulty. By isolating the specific effects of mindfulness training on ERPs associated with enhanced attention and cognitive control, we can capture an electrophysiological time course of ERPs indexing early visual processing, selective attention, conflict detection, stimulus evaluation and error processing that is unique to mindful attention regulation, particularly when the cognitive control system is challenged.

We used EEG to record ongoing neural activity during a modified Digit Stroop task, before and after two weeks of daily mindfulness meditation practice or guided visual imagery practice. By manipulating task difficulty and contrasting the specific practice of sustaining focus, disengaging from distractions, and redirecting attention in mindfulness meditation with the passive attention regulation in guided visual imagery meditation, we sought to isolate the electrophysiological indices of mindfulness attention regulation when the cognitive control system is sufficiently challenged. Although we did not observe any behavioural differences between groups across time (i.e., training effects), we found electrophysiological differences that show the effects of mindfulness training on early perceptual processing, stimulus-driven attentional capture, and conscious evaluation of stimuli. After two weeks of daily practice, the mindfulness meditation group showed a larger occipital-parietal P1 amplitude in the right hemisphere, reflecting enhanced sensory processing, and earlier posterior P3b peak latencies on congruent and incongruent trials, reflecting faster conscious evaluation of all stimuli. In contrast, the frontal P3a peak latency was significantly delayed in the active control group, while there was no change observed in the mindfulness group, reflecting a resistance to automatic capture of stimulus-driven attention after mindfulness training when task demands were increased. We also used the MAAS, FFMQ and FMI to examine changes to self-reported levels of mindfulness after training. While there were no significant differences observed in the MAAS, both groups significantly increased on the FFMQ-Observe and FFMQ-Nonreactivity facets, and significantly decreased on the FFMQ-Nonjudging facet after training. However, only the mindfulness group showed a significant increase on the FMI, confirming higher levels of state mindfulness after training.

P1 and N1: Early Sensory Processing Sensitive to Selective Attention

Both P1 and N1 components are related to early sensory processing and are modulated by focus of attention (Debruille et al., 2019; Ahumada-Mendez et al., 2022). Although the P1 and N1 are not indices of cognitive control, we hypothesized that the mindful practice of focusing and sustaining attention on task-relevant information would enhance early sensory processing sensitive to selective attention, resulting in larger P1 and N1 components. While previous research has demonstrated that the P1 and N1 are sensitive to spatial and feature-based selective attention and are modulated by focus of attention in the hemisphere contralateral to the stimulus location (Ahumada-Mendez et al., 2022; Debruille et al., 2019; Hillyard & Münte, 1984; Mangun & Hillyard, 1995; Zhang & Luck, 2009), we did not have any a priori predictions of laterality effects because the stimuli were presented centrally on the screen in this study. However, we observed a significantly larger P1 amplitude in the right hemisphere after mindfulness training. The right lateralization of the P1 is consistent with global/local studies that show a larger P1 amplitude associated with global processing biases during the Navon task (Navon, 1977; Delis et al., 1986; Evans et al., 2000; Lamb et al., 1989). In the Navon task, stimuli have a hierarchical structure and consist of both global and local features (e.g., a large global letter is formed by the spatial arrangement of small local letters). While global and local information can be processed in both hemispheres, evidence from behavioural (Blanca et al., 1994; Hughes et al., 1996; Kitterle et al., 1990; Lamb & Robertson, 1989; Sergeant, 1982), neuroimaging (Fink et al., 1996; Fink et al., 1997; Heinze et al., 1998; Heinze et al., 1989; Lamb et al., 1990) and neuropsychological studies (Delis et al., 1986; Lamb et al., 1989; Lamb et al.,

1990) show a bias for global processing in the right hemisphere and for local processing in the left hemisphere. In the present study, the Digit Stroop stimuli are presented in the center of the screen as a horizontal string of digits (e.g., 55555) and the task requires participants to identify the number of digits, while ignoring the identity of digits. Although unintended in task design, in order to respond correctly by identifying the number of digits while ignoring the identity of digits, global processing of stimuli is advantageous on all trial types, particularly on incongruent trials where there is greater interference between global and local stimulus features (i.e., the number of digits and identity of digits are conflicting). Seeing that P1 amplitudes in the right hemisphere were significantly larger in the mindfulness group for all trial types, irrespective of congruency, the deliberate practice of focusing and sustaining attention on task-relevant information may have facilitated an adaptive global processing strategy in the mindfulness group after two weeks of daily training, but only when task difficulty is increased. In our previous study where difficulty was not experimentally manipulated on the Digit Stroop task, no differences in P1 amplitude or latency were observed between groups after training (Chapter 3). The left and right P1 peak latencies were earlier in the ERP waveforms of the mindfulness group relative to the active control group before and after training, reflecting an unexpected group difference that was not a consequence of mindfulness training.

Group differences also emerged in the N1 component. Overall, N1 mean and peak amplitudes were larger in the mindfulness group in both the left and right hemispheres. Similar to our previous findings, larger N1 mean and peak amplitudes were observed for both groups on incongruent trials compared to congruent trials (Chapter 3). However, novel to this study, we also observed that the N1 in the right hemisphere peaked significantly earlier after training for both groups. Overall, both groups had earlier N1 peak latencies after training. N1 amplitudes were also larger for incongruent trials compared to congruent trials across both hemispheres, regardless of group. This increased N1 amplitude is partially consistent with a study by Moore et al. (2012) where an increased negative deflection in occipital-parietal regions was observed on the colour-word Stroop task after mindfulness training. However, this relative increase over occipital-parietal regions occurred in both hemispheres after meditation training, irrespective of congruency. A study by David et al. (2011) also observed an increased N1 amplitude across various occipital-parietal electrode sites during a Stroop matching task, where participants compared the ink colour of a coloured word with the meaning of a colour-word in white ink. They observed a larger N1 amplitude for congruent stimuli compared to incongruent stimuli, particularly when the two task stimuli were presented simultaneously. This provides evidence of early selection processing in a Stroop-like paradigm that is sensitive to temporal modulations of early attention. Relative to guided visual imagery training, our results do not provide strong evidence that early sensory processing is modulated uniquely by mindfulness training. However, future studies should continue to explore the impact of mindful attention regulation on early sensory processing sensitive to selective attention.

N2: Conflict Detection, Conflict Monitoring and Inhibition

In our previous study using an unmodified Digit Stroop task, differences in the N2 amplitude for congruent and incongruent trials dissipated after mindfulness training (Chapter 3). Contrary to our hypothesis, we did not observe any modulations of the N2 as a function of mindfulness training when task difficulty was manipulated. Overall, N2 amplitudes were larger for incongruent trials compared to congruent trials in both groups after training, suggesting greater detection, monitoring or inhibition of conflict on incongruent trials relative to congruent trials. Unsurprisingly, the N2 peak latency was also earlier after training for both groups, irrespective of congruency. This suggests that both groups were faster at processing conflict in congruent trials relative to incongruent trials, particularly when stimulus duration was systematically decreased as accuracy on the task increased.

In longitudinal training studies that also used Stroop interference paradigms, an increase in N2 amplitude was observed post-intervention (Malinowski et al., 2017; Moore et al., 2012). However, Malinowski et al. (2017) used a population of older adults, where greater baseline deficits in cognitive control processes have been documented (Friedman et al., 2009; Friedman & Robbins, 2022). Therefore, compared to younger adults, the older adults in Malinowski et al. (2017) may have shown more improvement after 8 weeks of mindfulness training, particularly on a task designed to recruit executive control and emotion regulation simultaneously, thereby introducing various competing processes that are likely to elicit an increased N2 response. On the contrary, Moore et al. (2012) observed an increased N2 response on incongruent trials during the colour-word Stroop task after 16 weeks of mindfulness training in a population of healthy younger adults. While a longer period of mindfulness training may be required to observe an increased N2 amplitude, particularly on incongruent trials, their reported increase of a negative deflection that peaks between 160 and 240 ms over occipital-parietal regions of both hemispheres better fits the profile of an N1 component, rather than an N2 component. Finally, the reported increase of N2 amplitudes in both studies are relative to very different control conditions (an active control condition engaging in mental arithmetic calculations in Malinowski et al., 2017, waitlist controls who are not engaging in any cognitive training in Moore et al., 2012). Relative to these control conditions, the present study targeted conflict monitoring processes that are uniquely tied to the mindful practice of disengaging from task irrelevant features by using an active control group that engaged in the passive attention regulation of guided visual imagery, where no such deliberate disengagement of attention was cultivated. Therefore, increased N2 amplitudes may only be observed relative to control conditions that do not have comparable demands on conflict detection, conflict monitoring and inhibitory processes.

P3a: Stimulus-Driven Attentional Capture and Involuntary Allocation of Attention

Consistent with our hypotheses, the mindfulness group displayed greater resistance to automatic capture of stimulus-driven attention when task demands were decreased. While the frontal P3a peak latency for congruent and incongruent stimuli was significantly earlier in the active control group, there was no change observed in the mindfulness group, reflecting a greater capacity to disengage from involuntary allocation of attention to stimuli, particularly when task demands were increased. This result compliments our previous findings that showed a delayed P3a peak latency on incongruent trials during the unmodified Digit Stroop task, reflecting reduced involuntary allocation of attention to incongruent stimuli after mindfulness training (Chapter 3). However, in the present study, where stimulus duration was reduced to increase task difficulty, involuntary allocation of attention to stimuli occurred earlier in the active control group, while the mindfulness group maintained the same speed of stimulus-driven attentional processing, regardless of increasing demands on cognitive control. This is in line with the interpretation that mindfulness facilitates unbiased information processing by disengaging the attentional system from stimulus-driven activation (Verdonk et al., 2000). Taken together, these findings provide evidence that mindfulness training enhances cognitive control by disengaging or downregulating stimulus-driven attentional capture, particularly when cognitive control is challenged.

To our knowledge, only two other studies have examined the impact of mindfulness meditation on the anterior P3a component. Using a sample of meditators with 20 years of Vipassana meditation experience in a within-subject design, Cahn and Polich (2009) compared performance on an auditory oddball task after 30 minutes of mindfulness (Vipassana) meditation or 30 minutes of random thinking (mind-wandering). A lower P3a amplitude was observed for deviant tones during the meditative state relative to the mind-wandering state and this reduction in amplitude was positively correlated with frequency of meditation practice, providing strong evidence that mindfulness is associated with reduced stimulus-driven attentional capture. Although we did not observe modulations of P3a amplitude after mindfulness training, the disengagement of automatic stimulus-driven attentional capture during a meditative state relative to a mind-wandering state mirrors a similar pattern of disengagement observed after mindfulness training relative to guided visual imagery training.

In contrast, a recent longitudinal study by Incagli and colleagues (2020) compared cognitive control performance on an AX-continuous performance task (AX-CPT; Dias et al., 2003) after 8 weeks of Mindfulness Based Stress Reduction (MBSR) or 8 weeks of Pilates training. Increased P3a amplitudes were observed across all trial types after MBSR training relative to the active control group. The AX-CPT paradigm was used to test the dynamic interaction between proactive and reactive cognitive control mechanisms based on the Dual Mechanisms of Cognitive Control theory (DMCC; Braver et al., 2007). Larger P3a amplitudes have been previously observed in AX-CPT paradigms and are thought to reflect greater inhibition of prepotent responses (Morales et al., 2015). Rather than proactively disengaging the attentional system from stimulus-driven activation, MBSR training may have upregulated reactive control mechanisms, resulting in a late-correction process rather than an early selection process. Consistent with this view, the larger P3a amplitude was interpreted as increased efficiency of reactive cognitive control mechanisms after MBSR training. However, a typical MBSR program involves a variety of standardized attention regulation exercises, including sitting meditation, walking meditation, eating meditation, gentle movement, and body scan awareness (Kabat-Zinn, 1990). Although it's plausible that an 8-week MBSR program increased domain-general cognitive control, MBSR training was compared to Pilates training—a form of physical fitness that placed emphasis on performing correct and harmonious movements. Without an appropriate control group to contrast and compare precise cognitive processes, it is not clear which mindful attention regulation components of MBSR lead to increased efficiency of reactive cognitive control mechanisms (reflected by larger P3a amplitudes).

Nevertheless, this finding challenges the functional significance of the P3a peak latency observed in our study. Rather than proactively disengaging the attentional system from stimulus-driven activation, mindfulness training could have upregulated reactive control mechanisms that rely on detection and resolution of interference after its onset, resulting in late-correction processes that are only observed in subsequent ERP components. On the other hand, the early P3a peak latency observed in the active control group could reflect proactive control mechanisms that rely upon the anticipation and prevention of interference before it occurs, resulting in early selection and maintenance of task-relevant information.

P3b: Conscious Processing and Evaluation of Stimuli

As we predicted, the enhanced ability to deliberately disengage attention from task-irrelevant information (e.g., identity of digits) and redirect attention to relevant information (e.g., number of digits) after mindfulness training was associated with faster processing and evaluation of all stimuli, as reflected by earlier P3b peak latencies, irrespective of stimulus congruency.

Although some studies have shown no impact of mindfulness on the P3b (Malinowski et al., 2017; Norris et al., 2018), in general, mindfulness has been associated with increased P3b modulation when processing-task-relevant stimuli (Atchley et al., 2016; Delgado-Pastor et al., 2011; Smart et al., 2016) and decreased P3b modulation when inhibition of task-relevant information was required (Atchley et al., 2016; Howells et al., 2012; Moore et al., 2012; Slagter et al., 2007). This evidence supports the effect of congruency that was observed in both groups overall. P3b amplitudes were significantly larger for congruent trials, where both stimulus features (identity of digits and number of digits) correspond with the correct task-relevant response (number of digits), compared to incongruent trials, where greater inhibition of task-irrelevant features (identify of digits) is required. Although there were no differences in modulation of P3b amplitudes between the mindfulness group and the guided visual imagery group after training, the current results replicate our previous finding of earlier P3b latencies on the unmodified Digit Stroop task after mindfulness training (Chapter 3). This pattern of results provides strong evidence that mindfulness training enhances speed of conscious processing and evaluation of stimuli, rather than influencing the allocation of attentional resources.

ERN and Pe: Error Processing and Performance Monitoring

We hypothesized that the deliberate disengagement of elaborative processing (e.g., judgment or reactivity to errors) and redirection of attention to relevant task information after mindfulness training would facilitate “nonjudgmental acceptance” during error commission, resulting in modulations of the ERN and Pe that reflect reduced vigilance and conscious awareness of errors. However, we did not observe any differences in modulation of the ERN or Pe between groups after training. Overall, both groups showed larger ERN amplitudes on congruent trials compared to incongruent trials, reflecting increased attentiveness to errors committed on “easier” congruent trials relative to more “difficult” incongruent trials, consistent with what is often seen in ERN studies. Similarly, no differences in conscious error processing were observed between groups after training. Overall, Pe amplitudes were significantly larger for congruent trials than incongruent trials, suggesting both groups experienced greater conscious awareness after committing errors on the easier congruent trials. We also observed a delayed peak latency for congruent trials relative to incongruent trials in both groups, suggesting deferred or prolonged conscious processing of congruent errors. This congruency effect in Pe amplitude and peak latency likely reflects the difference in saliency and rumination of congruent errors versus incongruent errors. Committing errors on congruent trials where stimulus features are compatible and more likely to activate the correct response are much more salient and prone to rumination compared to error commission on more difficult incongruent trials, where incompatible stimulus features are competing and more likely to activate incorrect responses.

In our previous study, the active control group became faster at automatic detection of errors after training while the mindfulness group showed a delayed index of automatic error detection after mindfulness training (Chapter 3). In the current study, we manipulated task difficulty by increasing or decreasing stimulus duration every 20 trials, identifying a threshold for each participant where cognitive control was sufficiently challenged to better detect deployment of attentional processes associated with mindfulness training. If participants were too slow at responding to a stimulus (response time exceeded stimulus duration), a warning appeared on the screen that read, “Too Slow!!!”. In this way, task difficulty was maintained, and participants were required to adjust the speed of response accordingly. By maintaining accuracy between 70% and 80%, thereby increasing the probability of errors, we expected to see greater differences in error processing. However, no differences in the ERN and Pe were observed between groups. By manipulating task difficulty in this way, it's possible that we also manipulated affective and motivational significance sufficiently in both groups, making all errors too salient to detect more nuanced differences between mindfulness and guided visual imagery training.

While some previous studies show an increased ERN associated with mindfulness (Teper & Inzlicht, 2012; Smart & Segalowitz, 2017; Eichel et al., 2017; Saunders et al., 2016) other studies show decreased or no change (Larson et al., 2013; Schoenberg et al., 2014; Bing-Canar et al., 2016). Likewise, the impact of mindfulness on Pe modulation is unclear, with some studies showing an increased amplitude (Schoenberg et al., 2014), some studies showing a decreased amplitude (Larson et al., 2013) while some studies showed no change (Teper & Inzlicht, 2012; Smart & Segalowitz, 2017; Saunders et al., 2016; Bing-Canar et al., 2016). While the current study did not observe the effects of mindfulness training on electrophysiological indices of performance monitoring when task difficulty was increased, future replications of this work are necessary to understand the relationships between mindful attention regulation and error monitoring when demands on cognitive control are challenged.

Additional Findings

By using a task designed to heighten and sufficiently challenge cognitive control demands, we predicted between group differences in behavioural outcomes, including faster response times, greater accuracy, reduced Stroop interference, and decreased post-error slowing (PES) following mindfulness training. However, we did not observe any behavioural differences between groups after training. Overall, both groups showed faster response times, reduced post-error slowing (PES) and a smaller Stroop interference effect after training, suggesting that increasing task difficulty may have enhanced overall engagement and motivation similarly in both groups, improving behavioural performance with practice over time.

This is supported by the significant increase in self-reported FFMQ-Observe and FFMQ-Nonreactivity facets that were observed in both groups after training. The FFMQ-Observe facet measures the ability to notice or attend to internal and external experiences such as sensations, cognitions, and emotions, while the FFMQ-Nonreactivity facet measures the ability to disengage from elaborative processing of thoughts or emotions that arise in awareness (Baer et al., 2006). Therefore, the significant increase in self-reported FFMQ-Observe and FFMQ-Nonreactivity facets could reflect a greater ability to attend to task stimuli and perceive information without reaction, facilitating greater efficiency when processing varying degrees of conflict as seen by faster response times, reduced post-error slowing and a smaller Stroop interference effect in both groups after training. This is supported by our previous study, where the FFMQ-Observe and FFMQ-Nonreactivity facets were significant predictors of increased accuracy and reduced Stroop interference on the titrated Digit Stroop task, respectively (Chapter Two). This is also in line with previous evidence where the FFMQ-Observe facet has been associated with heightened perceptual awareness and better behavioural performance on perceptual tasks (visual working memory and temporal order judgment tasks) while the FFMQ-Nonreactivity facet has been associated with reduced Stroop interference (Anicha et al., 2012).

Surprisingly, both groups also showed a significant decrease in the self-reported FFMQ-Nonjudging facet after training, suggesting a decreased ability to take a non-evaluative stance towards thoughts and emotions that arise in awareness. Although this was not expected, particularly after mindfulness training, this decrease in self-reported FFMQ-Nonjudging could explain the absence of ERN and Pe modulation after training, where both groups showed similar neurophysiological responses to error processing over time. If both groups decreased in their ability to take a non-evaluative stance towards errors (i.e., increased judgment or evaluation in response to error commission), it is possible that any training or practice effects could not overcome the saliency of error processing that persisted or increased over time.

While there were no behavioural differences observed between groups after training, the mindfulness group showed a significant increase on the FMI, confirming higher levels of state mindfulness after training. Coupled with the observed electrophysiological differences that reflect enhanced sensory processing, faster conscious evaluation of all stimuli and resistance to stimulus-driven attentional capture, this suggests that the mindfulness group was processing information more efficiently after mindfulness training, even though behavioural differences in improved performance were not different among groups. This provides further evidence that mindfulness training alters neural activity reflected in ERPs associated with enhanced cognitive control, even when differences in behavioural outcomes are not observed.

Limitations

To completely isolate and discern the effects of mindfulness training on cognitive control, the inclusion of an inactive control group is necessary to contrast both mindful attention regulation in the meditation group and passive attention regulation in the active control group. Due to logistical constraints, we were not able to compare mindfulness training and guided visual imagery training with an inactive control group that did not engage in any kind of attention regulation between pre-test and post-test sessions. Without an inactive control group, we cannot confirm whether the guided visual imagery influenced cognitive control processes in some way, by virtue of engaging domain general attentional mechanisms. This could explain why the main electrophysiological findings reflected changes in speed of processing (reflected by peak latencies) rather than modulations in allocation of resources (reflected by mean and peak amplitudes).

Due to scheduling constraints, limited enrollment and drop-outs, our study consisted of small sample sizes. This introduced higher impact of individual variance in the ERP data, placing emphasis on within group differences rather than between group differences when pre-existing group differences emerged in the data. In addition, as this study was part of a larger longitudinal design, participants completed a number of supplementary tasks pre- and post-training. Therefore, it’s possible the current results are confounded by states of cognitive fatigue and decreased vigilance, particularly post-training.

Finally, by manipulating stimulus duration to maintain accuracy at 70%–80%, we were able to examine the electrophysiological indices of mindfulness attention regulation when the cognitive control system was sufficiently challenged. However, by manipulating accuracy on the Digit Stroop task, we also manipulated the speed-accuracy trade-off (Wickelgren, 1977). Therefore, we cannot interpret behavioural measures, such as response time, in the same way as speeded tasks where accuracy is not manipulated.

Future Directions

Mindfulness is typically studied in three different ways: as a state evoked by brief practice, as an outcome of long-term formal practice, or as an inherent disposition or psychometric measure that varies across individuals. Few studies, however, take individual differences in dispositional mindfulness into account before evaluating the outcome of state or trait-dependent changes of mindfulness practice, leading to inconsistent interpretations on the effects of mindfulness practice in the scientific literature. This is important when studying the relationship between overlapping constructs like mindfulness and cognitive control, where individual differences in dispositional mindfulness can explain variation in a set of processes measured by electrophysiological and behavioural indices of cognitive control. This highlights the importance of examining how dispositional, psychometric properties or trait-like outcomes of long-term practice can influence the impact of mindfulness inductions on measures of executive attention and cognitive control. Future studies should consider how individual differences in dispositional mindfulness or other psychometric measures mediate or moderate the impact of mindfulness training on cognitive control.

Although the main purpose of this study was to investigate changes to electrophysiological indices of cognitive control, by manipulating task demands and increasing task difficulties, we were theoretically motivated to explore whether challenging the cognitive control system would also affect early sensory processing sensitive to selective attention. To our knowledge, this is the first mindfulness study that found evidence of enhanced early sensory processing during a cognitive control task. Future studies will be needed to replicate these findings and extend their analyses to include other neural markers that could be influenced when the cognitive control system is challenged such as the prefrontal negativity or pN, an index of proactive inhibition that has been recently examined in Stroop paradigms (Berchicci et al., 2012; Bianco et al., 2021; Di Russo et al., 2016) or the Correct Response Negativity (CRN), which is a negative deflection that occurs when there is uncertainty in the correctness of a given response, or when a stimulus elicits sub-threshold incorrect response activation before completing a correct response (Coles et al., 2001; Ford, 1999; Falkenstein et al., 2000; Vidal et al., 2000).

Finally, it is not clear what prescriptive dose of mindfulness is required to observe differential effects in the underlying neural correlates of cognition and behaviour or whether these effects persist over time. While some studies show an impact after brief mindfulness inductions, other studies show little to no impact after longer interventions. For this reason, future studies should systematically vary the length of mindfulness training, from brief inductions to extended interventions, using carefully controlled longitudinal designs that examine both stimulus-locked and response-locked electrophysiological indices of cognitive control in expert meditators, novice meditators and I non-meditators.

Conclusion

This study utilized the high temporal resolution of ERPs to capture ongoing neural activity during a modified Digit Stroop task, before and after two weeks of daily mindfulness meditation practice or guided visual imagery practice. By manipulating task difficulty and contrasting the specific practice of sustaining focus, disengaging from distractions, and redirecting attention in mindfulness meditation with the passive attention regulation in guided visual imagery meditation, we were able to isolate the electrophysiological indices of mindfulness attention regulation when the cognitive control system was sufficiently challenged. Specifically, we found a larger occipital-parietal P1 amplitude in the right hemisphere after mindfulness training, reflecting enhanced sensory processing tied to global processing of stimuli. We also observed earlier posterior P3b peak latencies on congruent and incongruent trials in the mindfulness group, reflecting faster conscious evaluation of all stimuli. In contrast, the frontal P3a peak latency was significantly delayed in the active control group, while there was no change observed in the mindfulness group, reflecting a resistance to automatic capture of stimulus-driven attention after mindfulness training when task demands are increased. The inclusion of an active control group that contrasted mindful attention regulation with passive attention regulation was crucial in producing novel results that replicate and expand the emerging literature on the electrophysiology of mindfulness and cognitive control. The results of this study have important implications for our empirical understanding of cognitive control mechanisms involved in mindful attention regulation and its salutary effects on executive function.

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Chapter 5—Discussion

Swapna Krishnamoorthy

Research Problem, Aims and Objectives

The primary focus of this doctoral dissertation was to investigate the impact of mindfulness on behavioural and electrophysiological correlates of cognitive control using the high-temporal resolution of EEG to record event-related potentials in meditators as they adapted to varying cognitive control demands during two different variations of the Digit Stroop task. While numerous studies have examined the effects of mindfulness on cognitive control, inconsistent findings have made it unclear whether mindfulness is always associated with enhanced cognitive control performance. One explanation for this discrepancy is that individuals vary in dispositional mindfulness—the inherent propensity to engage in mindful states (Brown & Ryan, 2003; Brown et al., 2007; Kiken et al., 2015). However, many studies do not take dispositional mindfulness into account and therefore cannot rule out pre-existing differences in individuals' ability to engage in mindful attention regulation. Furthermore, the effects of mindfulness on cognitive performance may not be observable unless task demands are sufficiently challenged to detect state-dependent, experience-dependent or trait-dependent mindfulness effects on cognitive control. While an emerging body of electrophysiological literature has attempted to disentangle these discrepant findings by examining the underlying neural mechanisms of mindfulness and cognitive control, studies vary greatly in experimental design, often lacking effective control conditions to isolate key components of mindful attention regulation hypothesized to influence electrophysiological indices of cognitive control. Within this limited literature, no studies examine both stimulus-locked and response-locked event-related potentials in a carefully controlled longitudinal design using a population of healthy young adults, particularly in experimental contexts where task difficulty is manipulated to challenge cognitive control demands for each individual.

Therefore, this doctoral thesis aimed to validate and justify the use of a modified Digit Stroop task designed to vary cognitive demands by establishing an empirical relationship between the construct of dispositional mindfulness and behavioural indices of the Digit Stroop task within two experimental contexts: when task difficulty was not manipulated (non-titrated) and when task difficulty was increased (titrated). I then sought to identify precise neural mechanisms underlying the empirical relationship between mindfulness and cognitive control by introducing a novel active control training condition (guided visual imagery meditation) that contrasts passive attention regulation with the focused attention regulation in mindfulness meditation. In doing so, I examined changes to stimulus-locked and response-locked ERPs first during the non-modified Digit Stroop task after two weeks of daily training. Finally, I sought to replicate these findings and examine changes to these electrophysiological indices of cognitive control, when the cognitive control system was challenged by increasing task difficulty using the titrated Digit Stroop task.

Summary of Key Findings

Chapter Two examined the overlapping constructs of mindfulness and cognitive control by establishing an empirical relationship between self-reported dispositional mindfulness (MAAS; Brown & Ryan, 2003; FFMQ; Baer et al., 2006) and behavioural indices of cognitive control in two variations of the Digit Stroop task designed to vary demands on executive function. I specifically hypothesized that high levels of dispositional mindfulness, measured by total MAAS and FFMQ scores, would predict better cognitive control as measured by faster response times, greater accuracy, reduced post-error slowing, a smaller Stroop interference effect and minimized sequential congruency effects when demands on cognitive control were increased using the titrated task and therefore more readily detected in this high functioning sample of healthy young adults. I also examined which FFMQ facets (*Observing, Act with Awareness, Describing, Nonjudging of Inner Experience* and *Nonreactivity to Inner Experience*) predicted behavioural indices of cognitive control, and if they were sensitive to varying cognitive control demands between experiments.

As hypothesized, the main findings of Chapter Two show that facets of self-reported dispositional mindfulness are only predictive of cognitive control performance when these processes are sufficiently challenged by manipulating task demands. Specifically, in Experiment 1, where task difficulty was not manipulated, measures of dispositional mindfulness were not associated with any indices of cognitive control performance. In Experiment 2, where cognitive control demands were challenged, the MAAS significantly predicted a reduced Stroop interference effect, while total FFMQ significantly predicted a smaller Stroop interference effect and greater accuracy on incongruent trials. Additionally, only the *Nonreactivity to Inner Experience* facet significantly predicted a smaller Stroop interference effect while the *Observing* facet significantly predicted accuracy on congruent and incongruent trials. These findings support the empirical relationships between dispositional mindfulness and cognitive control and highlight the importance of sufficiently challenging executive functions to detect mindfulness-related changes to cognitive control performance.

Chapter Three sought to identify neural markers of cognitive control specifically associated with mindfulness by contrasting components of mindfulness attention regulation training with components of passive attention regulation training using a novel active control condition (guided visual imagery meditation). Specifically, I examined changes to stimulus-locked and response-locked electrophysiological indices of cognitive control after two weeks of daily 20-minute mindful attention regulation training compared to two weeks of daily 20-minute passive attention regulation. Compared to the passive attention regulation in guided visual imagery meditation, the specific practice of sustaining focus, disengaging from distractions and redirecting attention in mindfulness meditation was hypothesized to change neural activity that would be captured in unique changes to ERP markers of early sensory processing (P1 and N1), conflict detection (N2), stimulus-driven attentional capture (P3a), conscious stimulus evaluation (P3b) and error monitoring (ERN and Pe).

After two weeks of daily practice, the mindfulness meditation group showed a smaller difference between N2 amplitudes for congruent and incongruent trials, reflecting increased efficiency in conflict detection and monitoring of stimuli with varying degrees of cognitive interference, delayed P3a latency for incongruent stimuli, reflecting delayed automatic capture of attention by incongruent stimulus features, earlier P3b latencies for both congruent and incongruent stimuli, reflecting faster conscious evaluation of all stimuli, and delayed ERN latency, reflecting delayed automatic detection of all errors regardless of congruency. These findings demonstrate the impact of mindfulness training on the neurophysiological processes underlying various aspects of executive function and cognitive control by capturing an information processing timeline from the time of stimulus presentation to the time of response completion. The inclusion of an active control group designed to contrast mindful attention regulation with passive attention regulation was fundamental in producing novel results that expand the limited literature on the electrophysiology of mindfulness and cognitive control.

Chapter Four compared and contrasted changes to these neural markers of cognitive control after mindfulness training or active control training when cognitive control processes were sufficiently challenged on a task designed to manipulate difficulty. Critically, I examined how two weeks of daily mindfulness training impacted electrophysiological correlates of cognitive control when task difficulty was manipulated and cognitive control processes were sufficiently challenged. By manipulating task difficulty and comparing mindfulness training with the novel active control group in the same carefully controlled longitudinal design, this chapter sought to replicate and extend the findings from Chapter Three. Specifically, by increasing difficulty, I predicted behavioural outcomes associated with enhanced cognitive control after mindfulness training, including faster response times, greater accuracy, reduced Stroop interference, and decreased post-error slowing, that were not observed in Chapter Three.

Although no behavioural differences were observed between training groups across time, there were electrophysiological differences that show the effects of mindfulness training on early perceptual processing, stimulus-driven attentional capture, and conscious evaluation of stimuli when cognitive control processes were challenged. After two weeks of daily practice, the mindfulness meditation group showed a larger occipital-parietal P1 amplitude in the right hemisphere, reflecting enhanced sensory processing, and earlier posterior P3b peak latencies on congruent and incongruent trials, reflecting faster conscious evaluation of all stimuli. In contrast, the frontal P3a peak latency was significantly delayed in the active control group, while no change was observed in the mindfulness group, reflecting a resistance to automatic capture of stimulus-driven attention after mindfulness training when task demands are increased. By manipulating task difficulty and contrasting the specific practice of sustaining focus, disengaging from distractions and redirecting attention in mindfulness meditation with the passive attention regulation in guided visual imagery meditation, I reported novel changes to electrophysiological indices of mindfulness attention regulation when the cognitive control system was sufficiently challenged.

Interpretations and Implications of Key Findings

As mentioned in Chapter One, mindfulness is typically operationalized as a state invoked by brief induction, as a training outcome of continued formal practice, or as an inherent disposition or trait that varies across individuals. Few studies, however, take individual differences in dispositional mindfulness into account before evaluating the outcome of state or experience-dependent changes of mindfulness practice. Furthermore, any state or experience-dependent effects may not be detected unless cognitive control is adequately challenged, contributing to discrepancies in the literature. If individuals vary in their baseline capacity to override prepotent responses to task demands (e.g., overriding the reflexive tendency to name the *identity* of digits in an array when the task requires correctly identifying the *number* of digits in the array), differential effects of cognitive control may not be detected unless those capacities are pushed to their limits for each individual. While the behavioural findings from Chapter Two cannot confirm whether individuals were pushed to the limits of their cognitive control capacity or if they changed cognitive control strategies in this experimental design, the manipulation of task difficulty captured behavioural performance that corresponded with self-reported mindfulness. After manipulating the Digit Stroop task to maintain accuracy at 70–80%, self-reported MAAS and FFMQ total scores significantly predicted a smaller Stroop interference effect, while the FFMQ total score significantly predicted greater accuracy on incongruent trials. The results also revealed that the *Nonreactivity* facet significantly predicted a smaller Stroop interference effect, while the *Observing* facet significantly predicted greater accuracy on congruent and incongruent trials. The findings from this chapter show that overall dispositional mindfulness is associated with a smaller difference in response time to stimuli with varying degrees of cognitive interference, reflected by reduced Stroop interference. This suggests that individuals with a high degree of dispositional mindfulness are less impacted by the added challenge of conflict on incongruent trials, even when task difficulty is increased. Similarly, the ability to disengage from elaborative processing of thoughts or emotions that arise in awareness (measured by the *Nonreactivity* facet) was associated with a smaller Stroop interference effect. This suggests that the ability to perceive information without reaction facilitates a greater capacity to process high degrees of conflict in the same way as stimuli with no conflict. Additionally, the ability to notice or attend to internal and external experiences such as sensations, cognitions and emotions (measured by the *Observing* facet) facilitated greater accuracy on congruent and incongruent trials. This suggests that greater capacity in observing information (internally and externally) facilitates a greater capacity to respond to goal-oriented information accurately. Taken together, overall dispositional mindfulness allows individuals to process varying degrees of cognitive interference similarly and with greater accuracy by heightening observations of internal and external information during current experiences and decreasing reactivity to any irrelevant information (e.g., thoughts or emotions) that may arise during those experiences, particularly in the face of conflict. In other words, individuals with a high degree of dispositional mindfulness can process varying degrees of conflict more efficiently and accurately, even when cognitive control processes are challenged by increasing task demands.

The key findings from Chapter Two are partially in line with previous studies of dispositional mindfulness and cognitive performance. The ability to perceive contents that arise in awareness without reacting (measured by the *Nonreactivity* facet) and taking a non-evaluative stance towards them (measured by the *Nonjudging* facet) have also been associated with reduced Stroop interference (Anicha et al., 2012). While this finding was interpreted as a greater ability to upregulate or downregulate the cognitive control system when it was contextually adaptive, I argue that the nonreactive and non-evaluative stance towards information that arises in awareness allows individuals to experience less reactivity or judgment on incongruent trials that have higher degrees of conflict and greater cognitive interference. In other words, rather than upregulating or down-regulating control processes, mindfulness may instead facilitate greater efficiency in processing varying degrees of conflict by not reacting or evaluating the conflict. The *Observing* facet has been associated with better performance on a visual working memory task and temporal order judgment task (Anicha et al., 2012), supporting the interpretation that self-reported *Observing* scores are related to the mindful quality of heightened perceptual awareness, facilitating adaptive behavioural outcomes on perceptual tasks as well as tests of executive function.

In contrast, other studies that have examined the relationship between FFMQ and executive function report diverging results. For example, Josefsson and Broberg (2011) found that higher scores on the *Describing* facet significantly predicted a smaller Stroop interference effect, but no other significant relationships were found between the FFMQ and Stroop variables. While the *Describing* facet involves the ability to articulate internal experience with words, it is not clear how this self-reported ability relates to cognitive control processes that mediate the Stroop interference effect. This lack of association between attentional facets of FFMQ and behavioural outcomes of the Stroop task is supported by other studies that found no significant relationships between the FFMQ and Stroop performance (Lykins et al., 2012; Schmertz, 2009). This reinforces the use of modified Stroop tasks that manipulate difficulty and adequately challenge cognitive control processes in order to observe trait-dependent effects of mindfulness on cognitive control performance, as demonstrated by the series of studies included in this dissertation.

Unlike the FFMQ, the MAAS measures mindfulness as a unidimensional construct that focuses on the attention and awareness aspects of mindfulness, rather than the attitudinal components of acceptance and non-judgment (Baer, 2003). In line with this, studies have shown that the MAAS total score and the FFMQ subscale *Act with Awareness* (which is comprised of MAAS items) were moderately correlated with self-reported attentional control (Brown et al. 2013; Quaglia et al., 2016). In Chapter Two, the MAAS was only a significant predictor of smaller Stroop interference when participants' cognitive control processes were sufficiently challenged by maintaining accuracy at 70-80% in the manipulated version of the Digit Stroop task, but did not significantly predict any other response time variables as predicted, including post-error slowing or the sequential congruency effect.

The MAAS defines mindfulness as "present-centered attention-awareness" (Brown & Ryan, 2003). Rather than measuring different qualitative facets of the mindfulness construct, it is possible that unidimensional measures like MAAS are assessing overall attentional engagement, reflecting greater engagement on all trials of the Stroop task, regardless of congruency. In line with the conflict monitoring theory of cognitive control (Miller & Cohen, 2001; Carter, Braver, Botvinick, & Cohen, 1998), greater dispositional mindfulness may enhance overall attentional engagement in a way that contextually biases top-down attentional control to resolve varying degrees of conflict with similar response times. When conflict is detected, high overall attentional engagement in dispositional mindfulness could facilitate biasing of attention to relevant information (e.g., number of digits in an array) to override the prepotency of irrelevant information (e.g., identity of digits), leading to small differences between response times for stimuli with varying degrees of cognitive interference. Still, inconsistent evidence between single factor measures of dispositional mindfulness and performance on tasks of attention and executive function make this interpretation difficult to confirm. For example, when examining the relationship between various self-reported dispositional mindfulness measures and selective attention tasks, Schmertz and colleagues (2009) found no significant association between the MAAS and performance on the cued single-trial Stroop task (Cohen et al., 1999). Instead, the MAAS was only significantly correlated with target omissions (an index of attentional lapses) on the Continuous Performance Test-II (CPT-II; Conners, 2002). If unidimensional measures like the MAAS are assessing overall attentional engagement, it's possible they may be better predictors of attentional lapses, rather than behavioural measures such as response times and accuracy on cognitive control tasks. In keeping with this hypothesis, it's been argued that the MAAS would be better characterized as a simple and direct measure of self-reported lapses in awareness rather than an attention and awareness scale (Cheyne et al., 2006; Grossman, 2011). This is supported by findings where the MAAS was a robust predictor of attentional lapses on the Sustained Attention to Response Task (SART; Robertson et al., 1997) and self-reported attention-related errors (Cheyne et al., 2006). A robust relationship between the MAAS and boredom proneness was also observed, revealing an association between the maintenance of attentional engagement with the environment and brief lapses of attention (Cheyne et al., 2006). Therefore, dispositional mindfulness measured by the unidimensional MAAS might reveal more about the overall ability (or inability) to engage the attentional system during goal-oriented tasks, better predicting *lapses* of attentional engagement rather than predicting behavioural outcomes associated with successfully engaging cognitive control processes.

It's important to note that most studies of mindfulness and executive function evaluate cognitive control performance by focusing on conflict trials themselves, rather than post-conflict performance. However, it is important to consider that rather than heightening attention and awareness to resolve conflict on *current* trials, mindfulness training may improve the ability to redirect attention *after* conflicting information or distraction is encountered and resolved (Lippelt et al., 2014). Evidence of differences in post-conflict resolution related to mindfulness is supported by a previous study in our lab where we observed a strong negative relationship between the MAAS and size of post-conflict slowing in a task-switching paradigm estimated by the size of bivalency effect (BE; Grundy et al., 2018; Meir & Rey-Mermet, 2012; Meier et al., 2009; Woodward et al., 2003). The MAAS also had less influence on response times for conflict trials themselves, suggesting that the MAAS may be more predictive of post-conflict recovery processes rather than conflict resolution. This supports the interpretation that salutary effects of mindfulness are not only limited to conflict resolution during an instance of cognitive interference, but may also influence control processes by facilitating rapid recovery after encountering conflict. In turn, this rapid post-conflict recovery can better prepare individuals with high levels of dispositional mindfulness to attend and respond to subsequent stimuli with varying degrees of conflict.

While studies of dispositional mindfulness are useful for understanding the convergence between constructs of mindfulness and cognitive control, they cannot identify precise cognitive control mechanisms involved in mindfulness. Therefore, in Chapters Three and Four, I used EEG to record event-related potentials (ERPs) during both the unmodified and modified Digit Stroop tasks to identify and observe changes to neural markers of cognitive control specifically associated with mindfulness after two weeks of daily practice. When performance on the unmodified Digit Stroop task was compared to the novel active control condition (guided visual imagery meditation) in Chapter Three, the mindfulness meditation group showed multiple electrophysiological changes after training, including efficiency in conflict detection and monitoring of stimuli with varying degrees of cognitive interference (attenuated congruency effect in N2 amplitudes), delayed automatic capture of attention by incongruent stimulus features (slower P3a latency for incongruent trials), faster conscious evaluation of all stimuli (earlier P3b latencies for congruent and incongruent trials) and delayed detection of errors (longer latency of ERN). When task difficulty was manipulated to increase demands on cognitive control in Chapter Four, the mindfulness group showed enhanced sensory processing associated with global processing of stimuli (larger P1 in the right hemisphere), faster conscious evaluation of all stimuli (faster P3b latencies) and resistance to automatic capture of stimulus-driven attention (no change in P3a latencies compared to the active control group).

The inclusion of the active control training group designed to contrast mindful attention regulation with passive attention regulation was fundamental in producing novel results that expand the current electrophysiological literature on mindfulness and cognitive control. Specifically, I revealed novel electrophysiological effects associated with *speed of processing* (peak latencies), rather than modulations in *allocation of resources* (mean and peak amplitudes), which are more commonly reported in the literature. Furthermore, no prior studies examine both stimulus- and response-locked ERPs in a sample of younger adults during two different executive function tasks of varying demands; thus, the current work has produced a novel set of findings that are unique to mindfulness training when cognitive control processes are contextually challenged.

Although the P1 and N1 waveforms are not typically studied as indices of cognitive control, I hypothesized that the mindful practice of focusing and sustaining attention on task-relevant information would enhance early sensory processing sensitive to selective attention, resulting in modulations of the P1 and N1 components after mindfulness training. While there were no significant changes to the P1 and N1 components between groups across time during the unmodified Digit Stroop task in Chapter Three, a larger P1 amplitude was observed in the right hemisphere after mindfulness training during the more challenging modified Digit Stroop task in Chapter Four. Previous research has shown that the P1 and N1 are modulated by focus of attention in the hemisphere contralateral to the stimulus location (Hillyard & Münte, 1984; Mangun & Hillyard, 1995), however there was no *a priori* prediction of laterality effects because all stimuli were presented centrally on the screen in the Digit Stroop tasks. Interestingly, the right lateralization of the P1 is consistent with global/local studies that show a larger P1 associated with global processing biases during the Navon task (Navon, 1977; Delis et al., 1986; Lamb et al., 1989; Evans et al., 2000). In the Navon task, stimuli have a hierarchical structure that consists of both global and local features (e.g., a large global letter is formed by the spatial arrangement of small local letters). In the Digit Stroop task, stimuli are presented in the center of the screen as a horizontal array of digits (e.g., 55555) and the task requires participants to identify the number of digits, while ignoring the identity of digits. If participants must identify the number of digits while ignoring the prepotent tendency to identify the identity of digits, a global processing strategy is advantageous on all trial types, particularly on incongruent trials where there is greater interference between stimulus features (i.e., the global and local features are conflicting). Although unintended in task design, the deliberate practice of focusing and sustaining attention on task-relevant information may have facilitated an adaptive global processing strategy after two weeks of daily mindfulness training, resulting in larger P1 amplitudes in the right hemisphere—indicative of increased global processing—which was not observed in the active control group after guided visual imagery training.

Although no significant differences in the N1 were observed between groups after training, both groups showed earlier N1 peak latencies in the right hemisphere and larger N1 amplitudes in both hemispheres for incongruent trials compared to congruent trials during the modified Digit Stroop task. This increased N1 amplitude is partially consistent with previous evidence that showed an increased negative deflection over occipital-parietal regions during the colour-word Stroop task after mindfulness training (Moore et al., 2012). However, this relative increase occurred bilaterally for congruent and incongruent stimuli and was compared to a group of waitlist controls who did not engage in any attentional training between testing sessions. Relative to guided visual imagery training, the results of Chapters Three and Four do not provide strong evidence that N1 processing is modulated uniquely by mindfulness training, however the increased P1 amplitude observed in Chapter Four provide strong justification for future studies to explore the impact of mindful attention regulation on early sensory processing sensitive to selective attention.

While most studies have shown that mindfulness has been associated with increased N2 amplitudes (Atchley et al., 2016; Malinowski et al., 2017; Moore et al., 2012; Norris et al., 2018; Quaglia et al., 2016), Chapter Three showed that the difference between N2 amplitudes on congruent and incongruent trials during the unmodified Digit Stroop task diminishes after two weeks of daily mindfulness training, suggesting an increase in efficiency between cognitive control processes that detect and monitor varying degrees of conflict in stimuli. Contrary to the hypothesis, when task difficulty was increased using the modified Digit Stroop task in Chapter

Four, modulations of the N2 as a function of mindfulness training were not observed. Instead, N2 amplitudes were larger for incongruent trials than congruent trials in both groups after training, suggesting a greater deployment of control processes were required to detect, monitor and inhibit conflict on incongruent trials when cognitive control processes were challenged by task demands. Unsurprisingly, the N2 peak latencies were also earlier after training for both groups, regardless of congruency. This suggests that both groups were faster at processing conflict after training, and that differences in cognitive control processes between groups may only be detected in later control processes when they are challenged by increasingly difficult task demands.

Previous longitudinal mindfulness training studies that also used a Stroop-interference paradigm have reported increased N2 amplitudes post-intervention (Malinowski et al., 2017; Moore et al., 2012). However, a number of substantial methodological differences must be accounted for. Malinowski et al. (2017) compared performance on an emotional-counting Stroop task in a group of older adults (ages 55 to 75 years) after 8 weeks of mindfulness meditation training or brain training exercises (active control training), while Moore et al. (2012) examined performance on a colour-word Stroop task in a group of healthy adults with 16 weeks of mindfulness meditation training compared to wait list controls. While both studies used a substantially longer length of training relative to our 2 weeks of training, Malinowski et al. (2017) used a population of older adults, where a greater prevalence of executive deficits could have increased the threshold for improvement on a task designed to recruit executive control and emotion regulation simultaneously, thereby introducing various competing processes that are likely to elicit an increased N2 response. On the other hand, Moore et al. (2012) compared colour-word Stroop performance after 16 weeks of mindfulness training using a population of healthy younger adults and observed an increased N2 response on incongruent trials. A longer period of mindfulness training may be required to observe an increased N2 amplitude, particularly on incongruent trials. Alternatively, Moore et al.'s results may be better interpreted as an altered N1, as their reported increase of a negative deflection that peaked between 160 and 240 ms over occipito-parietal regions of both hemispheres—described as an N2—better fits the profile of an N1 component. Finally, the reported increase of N2 amplitudes in both studies are relative to ERPs obtained from control participants engaging in mental arithmetic calculations (Malinowski et al., 2017) or waitlist controls who are not engaging in any additional cognitive training (Moore et al., 2012). Relative to these control conditions, our study targeted conflict monitoring processes that are uniquely tied to the mindful practice of disengaging from task irrelevant features, compared to the passive attention regulation of guided visual imagery where no such deliberate disengagement of attention was practiced. Therefore, increased N2 amplitudes may only be observed relative to control conditions that do not have comparable demands on cognitive control. However, in experimental contexts where overall demands on cognitive control are sufficiently challenged, differences in cognitive control may not be observed until later in the neural response timeline, reflecting differential recruitment of control processes related to involuntary allocation of stimulus-driven attention and conscious stimulus evaluation, rather than more controlled conflict detection or inhibition of irrelevant information.

Indeed, a number of studies have shown that mindfulness training modulates later control processes such as the P3a and P3b components. While only two mindfulness studies have examined the modulations of the P3a component, the findings from Chapter Three and Chapter Four extend current empirical interpretations of the impact of mindfulness on the cognitive control processes indexed by this component. Using a within-subject design, Cahn and Polich (2009) compared performance on an auditory oddball task after 30 minutes of mindfulness

(Vipassana) meditation or 30 minutes of random thinking (mind-wandering) in a sample of meditators with 20 years of Vipassana meditation experience. They observed a lower P3a amplitude for deviant tones after the meditative state relative to the mind-wandering state, providing strong evidence that mindfulness is associated with reduced stimulus-driven attentional capture. Although there were no modulations of P3a amplitude after mindfulness training in Chapter Three, the delayed P3a peak latency on incongruent trials during the unmodified Digit Stroop task reflects a similar pattern of resistance to automatic stimulus capture as found in Cahn and Polich (2009). This is also consistent with the results using the modified Digit Stroop task in Chapter Four, where the mindfulness group showed no change to P3a peak latencies, reflecting a greater capacity to disengage from involuntary allocation of attention to stimuli after mindfulness training, particularly when task demands are increased, while the guided visual imagery training control group showed significantly earlier P3a peak latencies for congruent and incongruent trials. While the reduced P3a amplitude associated with mindfulness is limited to this one study, a recent study by Incagli and colleagues (2020) examined ERPs associated with the AX-continuous performance task (AX-CPT; Dias et al., 2003) after 8 weeks of Mindfulness Based Stress Reduction training (MBSR; Kabat-Zinn, 1990) and observed increased P3a amplitudes across all trial types after MBSR training relative to the active control training group that received 8 weeks of Pilates training. Although this result appears contrary to the attenuated P3a amplitude observed in the study by Cahn and Polich (2009), larger P3a amplitudes have been observed in AX-CPT paradigms and are thought to reflect greater inhibition of prepotent responses (Morales et al., 2015). Based on the Dual Mechanisms of Cognitive Control (DMCC) theory by Braver and colleagues (2007), the AX-CPT paradigm has been used to test the dynamic interaction between proactive and reactive cognitive control mechanisms. Rather than proactively disengaging the attentional system from stimulus-driven activation, the authors proposed that MBSR training may have upregulated reactive control mechanisms, resulting in a late-correction process that led to an increased P3a amplitude. However, a typical MBSR program is a structured and standardized intervention that includes a variety of attention regulation exercises, including sitting meditation, walking meditation, eating meditation, gentle movement, and body scan awareness (Kabat-Zinn, 1990) while the Pilates active control condition involved physical fitness training that placed emphasis on performing correct and harmonious movements. Without an appropriate active control condition to contrast and compare precise cognitive control processes, it is not clear which mindful attention regulation mechanisms in the various MBSR exercises lead to increased efficiency of reactive cognitive control mechanisms, reflected by the larger P3a amplitudes. Nevertheless, both findings challenge the functional significance of the P3a observed in Chapter Three and Chapter Four. Rather than proactively disengaging the attentional system from stimulus-driven activation, mindfulness training may have upregulated reactive control mechanisms that rely on resolution of interference after its onset, resulting in late-correction processes that are observed as delayed P3a peak latencies during the unmodified Digit Stroop task in the Chapter Three, and slower P3a peak latencies relative to the guided visual imagery training group during the modified Digit Stroop task in Chapter Four. In contrast, the guided visual imagery active control group could have relied upon the activation and prevention of interference before it occurs, resulting in early selection and maintenance of task-relevant information, observed in the earlier P3a peak latencies during the modified Digit Stroop task.

Although these electrophysiological findings cannot confirm whether proactive or reactive control strategies were engaged during the Digit Stroop paradigm, the faster P3b peak latencies observed after mindfulness training support the interpretation that the mindfulness group proactively disengaged the attentional system from stimulus-driven activation, which in turn facilitated faster conscious processing and evaluation of all stimuli during the unmodified and modified Digit Stroop tasks. This is in line with the prediction that the deliberate disengagement of attention from task-irrelevant information (in this case, identity of digits) and redirection of attention to task-relevant information (number of digits) led to faster processing and evaluation of all stimuli after mindfulness training, irrespective of congruency. While some studies have shown no impact of mindfulness on the P3b component (Malinowski et al., 2017; Norris et al., 2018), mindfulness has generally been associated with increased P3b modulation when processing task-relevant stimuli (Atchley et al., 2016; Delgado-Pastor et al., 2011; Smart et al., 2016) and decreased P3b modulation was observed when inhibition of task-relevant information was required (Atchley et al., 2016; Howells et al., 2012; Moore et al., 2012; Slagter et al., 2007). This evidence supports the congruency effect that was observed in Chapters Three and Four, where P3b amplitudes in both groups were significantly larger for congruent trials where both stimulus features (identity of digits and number of digits) activate the correct task-relevant response (number of digits), compared to incongruent trials which require greater inhibition of task-irrelevant features (identity of digits). Although there were no differences in modulation of P3b amplitudes between groups after training, the significant changes to P3b latencies observed after mindfulness training during both variations of the Digit Stroop task provide strong evidence that mindfulness increases speed of conscious processing and evaluation of stimuli, rather than influencing allocation of attentional resources. These results from Chapters Three and Four are novel findings that have not yet been reported by any other published mindfulness studies.

Finally, the deliberate disengagement of elaborative processing and redirection of attention to task relevant information in mindfulness training was hypothesized to increase “nonjudgmental acceptance” when errors were committed, which would be reflected in modulations of the ERN and Pe that indicate reduced automatic detection and conscious awareness of errors after mindfulness training. Relative to the active control training group, the mindfulness group showed a delayed neural response to automatic error detection during the unmodified Digit Stroop task after mindfulness training, reflected by a slower ERN latency irrespective of congruency, suggesting less salience associated with having made any error. However, no differences in conscious error processing were observed between or within groups at the Pe. Overall, Pe peak amplitudes were larger for congruent trials than incongruent trials, suggesting that both groups were equally and consciously aware of committing errors on congruent trials more than incongruent trials. Contrary to the hypotheses, when task difficulty was increased with the modified Digit Stroop task in Chapter Four, there were no significant differences in the ERN or Pe between groups after training. Overall, both groups showed larger ERN amplitudes on the easier congruent trials compared to the more challenging incongruent trials, reflecting increased attentiveness to congruent errors (when errors are less expected and therefore more salient) relative to incongruent errors (when errors are more probable and therefore less salient). A similar pattern was observed in the Pe results when task difficulty was increased during the modified Digit Stroop task, suggesting that both groups experienced greater conscious awareness of committing errors on congruent trials. However, both groups showed a delayed peak latency for congruent trials relative to incongruent trials, reflecting deferred or prolonged conscious processing of the more salient congruent errors when task demands were increased.

The findings from Chapters Three and Four add to an already inconsistent body of findings regarding the impact of mindfulness on error monitoring. While some previous studies showed increased ERN modulation associated with mindfulness (Eichel et al., 2017; Saunders et al., 2016; Smart & Segalowitz, 2017; Teper & Inzlicht, 2013) other studies show decreased modulation or no change (Bing-Canar et al., 2016; Larson et al., 2013; Schoenberg et al., 2014). Likewise, the impact of mindfulness on Pe modulation is unclear, with some studies showing an increased Pe amplitude after mindfulness-based interventions (Schoenberg et al., 2014), some studies showing a decreased Pe amplitude after brief mindfulness induction (Larson et al., 2013) and some studies showing no modulation of the Pe associated with mindfulness (Bing-Canar et al., 2016; Saunders et al., 2016; Smart & Segalowitz, 2017;Teper & Inzlicht, 2013). Although there were no unique changes to electrophysiological indices of performance monitoring observed after mindfulness training when task difficulty was increased, the delayed response to automatic error detection during the unmodified Digit Stroop task in the experimental group versus control group suggests differential processing of errors after mindfulness training. Future replications of this work are necessary to clarify and confirm the impact of mindfulness training on the speed of error processing.

Limitations and Future Directions

One major limitation with studying dispositional mindfulness is whether the same "mindfulness" phenomenon is being measured by various psychometric assessments, particularly when several studies have demonstrated changes to dispositional mindfulness after mindfulness-based interventions (Hölzel et al., 2011; Jensen et al., 2012; Kilpatrick et al., 2011; Walach et al., 2006; Zeiden et al., 2011). If measures of dispositional mindfulness are sensitive to state or experience-dependent changes, the validity and reliability of self-reported mindfulness assessments comes into question. While dispositional mindfulness measures are useful in establishing an empirical relationship between mindfulness and related attentional constructs, it has been argued that trainees are likely to endorse mindfulness scale items differently at the end of training than at baselines (Grossman, 2011), warranting cautious interpretations based on experimental design. Furthermore, while self-report mindfulness measures rely on an individual's perception of their own capacity to engage in mindful abilities and attitudes, perceived mindfulness may not accurately map onto the attentional processes engaged during a mindful state. Since training or deploying attention more broadly also generalizes to a variety of functional demands (Posner & Rothbart, 2007), exercising attention in any capacity may also exercise mindful capacities, with or without formal mindfulness practice.

Therefore, in order to detect behavioural or electrophysiological effects of mindful abilities, experimental manipulations of task difficulty are necessary to challenge and detect changes to overlapping cognitive control processes, particularly in paradigms where performance is typically high. However, increasing difficulty by manipulating accuracy on the modified Digit Stroop task also manipulates the speed-accuracy trade-off (Wickelgren, 1977), limiting the interpretations of behavioural measures, such as response time, compared to speeded tasks when accuracy is not manipulated.

For these reasons, future studies should examine the impact of mindfulness on behavioural and electrophysiological indices of cognitive control within carefully controlled longitudinal designs that vary task demands across experimental paradigms.

To completely isolate and discern the effects of mindfulness training, however, the inclusion of an inactive control group is necessary to contrast mindful attention regulation and passive attention regulation in an active control group. Due to logistical constraints, this dissertation did not compare mindfulness training and guided visual training with an inactive control group that did not engage in any kind of attentional training between testing sessions. Therefore, without an inactive control group, it’s not possible to confirm whether the guided visual imagery training influenced cognitive control processes in parallel or opposite ways simply by engaging domain general attentional mechanisms. This could explain why the main electrophysiological findings reflected changes in speed of processing rather than modulations in allocation of resources and why there were no significant differences in behavioural measures between groups after training.

With limited electrophysiological literature examining the effects of mindfulness training on cognitive control, it was not clear what prescriptive dose of mindfulness was required to observe differential effects in the underlying neural correlates of cognitive control. While some studies showed an impact after brief mindfulness interventions, other studies showed little to no impact after longer interventions. For this reason, two weeks of daily mindfulness training was hypothesized to produce effects that would be observable under limited constraints on time and resources. However, future studies should systematically vary the length of mindfulness training, from brief inductions to extended interventions, examining both stimulus-locked and response-locked electrophysiological indices of cognitive control after trainings of different durations and assess whether they persist over time by inclusion of follow-up assessment.

Finally, it should be noted that the small sample sizes in Experiment 1 and Experiment 2 of Chapter Two limit generalizability of the results, and the very large number of dependent variables in tested in Chapter Three and Chapter Four increase the probability of making a type I error. It is also important to note that there is considerable overlap with Chapter Three and Four because they are two experiments with similar design using the same sample of participants within the same longitudinal training study. Future replications should consider increasing sample sizes when testing the relationship between dispositional mindfulness and cognitive control performance on both variations of the Digit Stroop task, as well as constrain the number of dependent variables tested when replicating the electrophysiological findings using the same sample of participants across two experiments within the same longitudinal design.

Concluding Summary

In this doctoral dissertation, I investigated the impact of mindfulness on behavioural and electrophysiological correlates of cognitive control using EEG to record ERPs in meditators as they adapted to varying cognitive control demands during two different variations of the Digit Stroop task. I first examined the overlapping constructs of mindfulness and cognitive control and showed that facets of self-reported dispositional mindfulness are only predictive of cognitive control processes when these processes are sufficiently challenged by manipulating difficulty and increasing task demands on a modified Digit Stroop task. I then identified electrophysiological markers of cognitive control that are specifically associated with mindfulness by contrasting components of mindful attention regulation training with components of passive attention regulation training using a novel active control condition (guided visual imagery meditation). Specifically, I demonstrated that two weeks of daily mindfulness training was associated with increased efficiency in conflict detection and monitoring of stimuli with varying degrees of cognitive interference, delayed automatic capture of attention by incongruent stimulus features, increased speed of conscious processing and evaluation of all stimuli, and delayed automatic neural reactivity to detection of errors, regardless of congruency. When task demands were manipulated to increase difficulty, I showed that mindfulness training was associated with enhanced early sensory and global processing of stimuli, resistance to automatic capture of stimulus-driven attention and faster conscious evaluation of all stimuli. The results of this body of work have important implications for our empirical understanding of mechanisms involved in mindfulness and their convergence with behavioural and electrophysiological correlates of cognitive control.

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