

The Influence of a Brief Mindfulness Induction on the Neural Response to Errors

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May 1, 2015

Abstract

The present study assessed the ability of a mindfulness meditation induction to affect the brain's error monitoring process, as indexed by the error-related negativity (ERN), error positivity (Pe), and error-related alpha suppression (ERAS). Participants ($n=37$) engaged in a mindfulness of breathing audio exercise or attended to a control listening exercise, depending on condition, to examine the influence of the mindfulness induction on error-related neural phenomena and performance on the Stroop test. Self-report measures of mindfulness, anxiety, and worry were also collected, including the Penn State Worry Questionnaire (PSWQ), the Five Facet Mindfulness Questionnaire (FFMQ), the State Trait Anxiety Inventory (STAI), and a brief survey assessing prior mindfulness experience. Analysis of participants' self-report, EEG, and performance data indicated no influence of the mindfulness induction on the ERN, Pe, or task performance. Instead, these two ERP components were related to individual self-report measures. However, ERAS did respond to the mindfulness induction, as participants in the mindfulness condition showed enhanced alpha power following control trials relative to controls. Together, these data suggest that neural responses to errors are predicted in complex ways by individual differences in mindfulness and anxiety. Findings are discussed as they relate to the adaptive role of mindfulness practices.

Introduction

Mindfulness has been previously described as “the awareness that emerges through paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience moment by moment” (Kabat-Zinn, 2003, pg. 145). Historically, mindfulness was developed from meditation techniques originating in Buddhist spiritual practices as a mechanism to undermine and alleviate personal suffering (Bishop et al., 2004). In a related vein, mindfulness is presently used as an approach for enhancing awareness and responding adaptively to mental processes that impact emotional distress and maladaptive behavior (Bishop et al., 2004).

Though the influence of mindfulness has been studied in relation to cognitive operations including attention and emotion regulation, other mental activities that may contribute to mental health have not received as much consideration. Specifically, there is a dearth of scientific literature devoted to the influence of mindfulness on executive functions, such as error monitoring. The meager literature that has examined this topic has yet to draw clear conclusions regarding the effect of trait mindfulness or a mindfulness intervention on the neural response to performance errors. Importantly, the way in which individuals respond to negative experiences more generally has the capacity to influence mental health and psychological well-being.

To address this gap in knowledge, the present study will examine the neural mechanisms underlying the influence of mindfulness meditation on error monitoring. The neural correlates of error that will be studied in relation to mindfulness include the error-related negativity (ERN), error positivity (Pe), and error-related alpha suppression (ERAS). These neural phenomena are reliably evoked in response to performance errors and will provide a clear index of error monitoring. A better understanding of the potential benefits of mindfulness on error monitoring will provide insight as to how mindfulness may be applied to individuals who suffer from

various mood and anxiety disorders, characterized by excessive rumination and maladaptive responses to negative life events.

History of Mindfulness

In order to develop a holistic and informed understanding of mindfulness, it is necessary to recognize its origins. Mindfulness is a non-judgmental form of consciousness, derived from Buddhist meditation practices. Though the conceptualization of meditation has evolved, both Buddhist views and current psychological adaptations of this practice assert that meditation is crucial to cultivate and improve mindfulness (Ivanovski & Malhi, 2007). Meditation has been defined by the Yoga Sutras as both a process involving the act of inward contemplation and a state of attentional focus toward an object (Ivanovski & Malhi, 2007).

Meditation can be divided into two different techniques, concentrative meditation and mindfulness meditation. Concentrative meditation practices involve centering attention on a mental object and narrowing the attentional focus to still the mind and improve clarity and awareness (Ivanovski & Malhi, 2007). Concentrative meditation styles include transcendental meditation, Oiyong Yoga, Yoga Nidra, Sahaja yoga, and Samantha meditations. On the other hand, mindfulness meditation involves expanding attention in a non-judgmental and nonreactive manner to increase awareness of current sensory, mental, and emotional experiences (Ivanovski & Malhi, 2007). In contrast to concentrative techniques, mindfulness meditation aims to expand awareness and the span of attention. Mindfulness forms of meditation include Zen and Vipassana meditations. In Vipassana meditation, the meditator acts as an observer of his or her thoughts and bodily sensations. This separation from internal processes facilitates a state of acceptance, non-reactivity, and nonattachment based on non-judgmental awareness of thoughts and somatic

sensations. Zen meditation emphasizes exclusion of irrelevant thoughts that threaten cognitive reasoning processes in an effort to attain a heightened state of consciousness.

While meditation is commonly rooted in Buddhist spiritual practices, there has been a gradual detachment of meditation from religious practice, which has allowed meditation to invade the scope of scientific investigation. Provided the historical use of meditation to relieve personal suffering, as well as research on the potential health benefits of meditation techniques, the scientific community has become increasingly interested in elucidating the mechanisms and manifestations of this type of mental training. Of particular importance to the present study is mindfulness, an outcome of meditation that has received considerable attention in psychological and neurophysiological research.

Definition and Operationalization of Mindfulness

Mindfulness is a multi-faceted concept, defined as the awareness that results from attending to the unfolding of experience moment-by-moment in a non-judgmental and purposeful manner (Kabat-Zinn, 1990). A fundamental aspect of mindfulness involves non-evaluative or receptive awareness and attention of physical sensations, perceptions, thoughts, imagery, and affective states (Bishop et al., 2004; Malinowski, 2013). This dispassionate and open awareness of mindfulness stands in opposition to restricted forms of consciousness, including rumination, or absorption in the past, or fantasies or anxieties about the future. These constrained modes of consciousness detract from being present in the moment in an accepting way (Brown & Ryan, 2003). Instead, mindfulness creates a bare display of experiences, nurturing an attitude of acceptance toward internal and external events (Bishop et al., 2004).

Increased research interest in mindfulness has given rise to a two-component operational definition of mindfulness proposed by Bishop and his colleagues at the University of Toronto

(2004). The first component of mindfulness involves self-regulation of attention that is maintained on immediate experience, allowing for enhanced recognition of mental events in the present moment. Mindfulness is ignited by orienting awareness to current experiences and observing and attending to the changing field of thoughts, feelings, and sensations from moment to moment, via regulation of the attentional focus. This process results in a feeling of increased alertness to present happenings and a subjective sense of being entirely present and alive in the moment.

The enhanced awareness that characterizes mindfulness also improves efficiency of attentional processes including sustained attention and attention switching. In contrast to the distraction of ruminative and elaborative trains of thought, the self-regulation of attention fostered by mindfulness promotes non-elaborative awareness of thoughts, feelings, and sensations as they occur. A common misconception of mindfulness is that it is a practice of thought suppression. Instead, mindfulness practice considers all thoughts and experiences as deserving of observation. However, once these are recognized, attention is returned to a current task and secondary elaborative processing of thoughts, feelings, and sensations that arise in the stream of consciousness is inhibited.

The second component of mindfulness offered by Bishop and his colleagues involves adopting a particular orientation characterized by curiosity, openness, and acceptance toward one's current momentary experiences. This aspect of mindfulness involves an active process of noticing each thought, feeling, and sensation that introduces itself to the stream of consciousness with an attitude of receptivity and acceptance. From this conception, mindfulness may be considered a process of relating openly with experience. Based on the acceptance component of mindfulness, embracing a stance of acceptance toward painful or unpleasant thoughts and

feelings should augment the psychological environment wherein these objects are experienced. Particularly important to the current study, negativity including emotional distress and adverse life episodes will be experienced as less unpleasant and threatening due to a mindset of acceptance. Thus, the subjective significance of negative experiences, such as performance errors, will be changed through implementation of mindfulness practices.

While an operational definition of mindfulness is certainly useful for fashioning a better understanding of mindfulness and implementing this conceptualization in psychological research on mindfulness, outlining the core components of mindfulness practice is also valuable. A recent Liverpool Mindfulness Model pioneered by Malinowski (2013) offers such a representation. This model incorporates 5 critical levels of mindfulness meditation practices: motivational factors, mind training, core mental processes, balanced mental stance or attitude, and positive outcome. The present study focuses on level three, which concerns how engagement in mindfulness practice develops and refines core mental processes to facilitate regulation of emotional and cognitive activities and how these processes may lead to positive outcomes for mental well-being.

Clinical Applications of Mindfulness

After multiple decades of research on the benefits of meditation techniques, there is emerging consensus that meditation practices facilitate improvement and recovery from a host of mental problems, including depression, anxiety, PTSD, ADHD, substance abuse, personality disorders, and antisocial behaviors (Pargament, 2013). At the forefront of this research is a heavy reliance on mindfulness meditation techniques in therapeutic practice, which has catalyzed a recent shift to the examination of mindfulness meditation in various mental health settings

(Ivanovski & Malhi, 2007). In recent years, mindfulness based techniques have been increasingly interwoven into clinical treatments by psychologists and psychiatrists.

The clinical applications of mindfulness typically involve a rigorous training program in meditation, channeling the production and application of mindfulness in an effort to improve well-being and mental health. Though therapeutic mindfulness techniques are often used to alleviate stress and treat mood disorders, they are not considered relaxation or mood management therapies. Instead, mindfulness approaches to psychological well-being are a form of mental training to reduce cognitive vulnerability to reactive thought systems that may otherwise increase stress and emotional distress, or that may trigger psychopathology (Bishop et al., 2004). Mindfulness-based tasks typically require the practitioner to attend to internal experiences including sensations, thoughts, and emotions, or to external stimuli, such as sounds (Ivanovski & Malhi, 2007). Importantly, the practitioner is required to observe these experiences, but not react to or evaluate them. Outcomes of these techniques typically involve changes in cognition and behavior, which lead to various physical and mental health advances. Mindfulness-based therapeutic techniques are particularly effective in the treatment of anxiety and depression, though mindfulness has also shown positive influences on an array of other affective and personality disorders (Ivanovski & Malhi, 2007).

Mindfulness and Anxiety. Interest in the clinical applications of mindfulness was spurred by the introduction of a mindfulness-based stress reduction (MBSR) program initially introduced by Jon Kabat-Zinn (1982) to manage chronic physical pain. More recently, MBSR has been employed in various clinical settings to treat emotional and behavioral disorders, including anxiety (Bishop et al., 2004). In a pioneering study by Jon Kabat-Zinn and his colleagues (1992) on the effectiveness of a MBSR program in the treatment of anxiety disorders, an 8-week group

training in mindfulness meditation was found to be successful in reducing symptoms of anxiety and panic among patients with generalized anxiety disorder, panic disorder, and panic disorder accompanied by agoraphobia. Moreover, results demonstrated maintenance of reductions in anxiety in these clinically anxious groups. In a three-year follow up of this study, Miller, Fletcher, & Kabat-Zinn (1995) examined the long-term effects of the MBSR program. These researchers observed preservation of gains obtained on the Hamilton and Beck anxiety and depression scales, the Hamilton panic scores, the number and severity of panic attacks, and on the Mobility Index-Accompanied and the Fear survey. Results of this follow-up study suggest that a time-limited, yet intensive group stress reduction intervention based on mindfulness meditation has long-term effects for patients diagnosed with anxiety disorders.

A recent meta-analysis of the influence of mindfulness-based therapy on anxiety supports findings from these studies, concluding a moderately effective improvement in anxiety from pre to post treatment in an overall sample of normal and clinical populations (Hofmann, Sawyer, Witt, & Oh, 2010). In clinical samples, these mindfulness interventions display a robust effect size for alleviating anxiety symptoms, confirming mindfulness as a promising therapy for treatment of anxiety disorders (Hofmann et al., 2010). Moreover, integration of acceptance-based treatments resembling mindfulness interventions with existing cognitive-behavioral treatments increase the efficacy and clinical significance of these approaches in patients with GAD (Roemer & Orsillo, 2002). Though MBSR programs display a clear positive influence on GAD and panic disorder with and without agoraphobia, mindfulness has also been used to treat other psychological distress disorders, namely depression and depressive relapse (Coffey, K. A., Hartman, M., & Fredrickson, B. L., 2010).

Mindfulness and Depression. A substantial amount of literature also advocates for the positive outcomes of mindfulness-based techniques on depression. While MBSR programs treat anxiety disorders, mindfulness-based cognitive therapy (MBCT) is used to remedy depression. MBCT combines training in mindfulness meditation with cognitive therapy, wherein practitioners increase awareness of their thoughts and feelings, and adopt a decentered perspective to dismiss internal experiences as “mental events”, rather than aspects of the self or accurate representations of reality (Teasdale, Segal, Williams, Ridgeway, Soulsby, & Lau, 2000). In one study, increases in mindfulness from a mindfulness exposure based cognitive therapy were associated with a linear decrease in self-reported and clinically assessed depression over the course of the intervention (Kumar, Feldman, & Hayes, 2008). These results support the use of MBCT to reduce depressive symptoms, as evidenced by a decline in depression and rumination in this sample.

Literature utilizing clinical samples also endorses the effectiveness of MCBT in recurrent depression and associated relapse. In a randomized control trial of patients with recurrent depression, the outcome of patients taking maintenance antidepressant medication (m-ADM) was compared to patients treated with MBCT (Kuyken et al., 2008). MBCT was more effective than treatment with m-ADM in reducing residual depressive symptoms and psychiatric co-morbidity, and in improving quality of life in both physical and psychological realms. Additionally, relapse rates were better among patients given MBCT over a 15-month epoch.

Important for the clinical use of MBCT are findings outlining a criterion for recurrent depression, in order for MBCT to effectively prevent depressive relapse. In one study, MBCT significantly reduced the risk of relapse in recurrently depressed patients with three or more previous episodes of depression, but not for patients with two or less previous episodes (Teasdale

et al., 2000). This trend has been replicated in a study comparing the effectiveness of treatment as usual (TAU) with the effectiveness of MBCT, as well as by a meta-analysis of the clinical features of mindfulness meditations (Ma & Teasdale, 2004; Chiesa & Serretti, 2010).

While substantial research has focused on elucidating the beneficial effects of mindfulness based-approaches on well-being, another line of research has focused on extrapolating the psychological and neurophysiological processes involved in mindfulness meditation. An enhanced knowledge of these mechanisms will enable the improvement of current mindfulness-based interventions, as well as the development of novel programs to treat additional psychological or physiological issues.

Mindfulness and Cognition

In order to achieve a better understanding of the psychological processes underlying mindfulness meditation techniques, it is necessary to examine the influence of mindfulness on cognition. Examination of the improvements in cognitive abilities due to mindfulness practices will provide insight into the way in which mindfulness therapies diminish maladaptive cognitive processes. Two particular cognitive control processes that may be central to improvements in psychological well-being and mental health are emotion regulation and attention.

Mindfulness and Emotion Regulation. Emotion regulation is a cognitive process that is thought to be augmented by mindfulness practices to produce positive outcomes for well-being. Importantly, one of the common motifs of mood disorders is the inability to adaptively regulate emotion, due to heightened negative reactivity and increased self-focus (Clark, Watson, & Mineka, 1994). Given the benefits of mindfulness-based treatments for depression, emotion regulation is a likely candidate for a cognitive process that these therapies improve. Indeed,

meditators are typically known to be expert emotional regulators (Perlman, Salomons, Davidson, & Lutz, 2010).

Typical strategies for emotion regulation are centered on reappraisal of aversive events in a more positive context, or on behavioral strategies to suppress emotionally expressive behavior (Gross, 2002). However, therapeutic forms of mindfulness promote increased tolerance of negative affect through two processes distinct from classic modes of emotion regulation: attention to present moment sensation to reduce cognitive elaboration, and equanimity, the disengagement from judgment of experiences (Farb, Anderson, & Segal, 2012). The transition to non-conceptual awareness that is cultivated through mindfulness practice appears to involve reduction of habitual evaluative processes and reallocation of attentional resources toward momentary awareness (Farb et al., 2012). The increased awareness and decreased evaluative processing results in an improved ability to handle negative emotions leading to enhanced well-being. Specifically, limiting cognitive elaboration in favor of momentary awareness appears to reduce automatic negative self-evaluation, increase tolerance for negative affect and pain, and to engender self-compassion and empathy in individuals with mood disorders (Farb et al., 2012).

Another possibility is that mindfulness attenuates early responses to emotionally salient stimuli before a subsequent emotional response occurs. Findings of a recent study demonstrate that mindfulness tempers neural responses in an early phase of affective processing as indexed by the late positive potential (LPP), an ERP component understood to reflect facilitated attention to emotional stimuli. (Brown, Goodman, & Inzlicht, 2012). In particular, dispositional mindfulness was found to be associated with lower LPP responses to both highly arousing and motivationally salient stimuli. These results suggest that mindfulness may act as a top-down

regulatory mechanism to dampen the arising of emotions before they have the opportunity to impact well-being (Brown et al., 2012).

Interestingly, emotional regulation may play a role in the relationship between mindfulness practices and enhanced executive control. In a study on the effect of meditation practice on executive control, experienced meditators displayed greater executive control, as indexed by fewer errors on the Stroop, and more emotional acceptance than controls (Teper & Inzlicht, 2013). Furthermore, mediation pathway models revealed that the influence of meditation practice on executive control was accounted for by heightened emotional acceptance. In other words, emotional acceptance was a mediator in the relationship between meditation experience and executive control (Teper & Inzlicht, 2013). These results suggest that heightened acceptance of emotional states, reflecting an improved ability to regulate emotion, may be a key reason that meditation improves executive functioning.

Mindfulness and Attention. Attention is another cognitive process that may underlie the mental health benefits of mindfulness practices, as training and refining attentional skills are central to most psychological and Buddhist conceptualizations of mindfulness practice (Lutz, Slagter, Dunne, & Davidson, 2008). In cognitive neuroscience, attention is thought to involve alerting, orienting, and executive control networks to support attentional functions (Posner & Petersen, 1990). Of particular importance to mindfulness practices are attentional functions including sustained attention, attentional shifts, and mind wandering, which are understood to rely on the alerting system, orienting network, and executive network, respectively (Malinowski, 2013). Cognitive and behavioral studies examining the influence of mindfulness meditation on attention support a constructive role of mindfulness in each of these attentional processes.

Mindfulness has been robustly linked to enhancements in sustained attention in both empirical research studies, as well as in meta-analytical reviews of the relationship between mindfulness and attention. In one study examining the influence of mindfulness on cognition, an intensive period of mindfulness meditation training was tied to improvements on performance measures of sustained attention (Chambers, Lo, & Allen, 2007). A similar study utilized the Wilkins' counting test as a measure of sustained attention, which involves presentation of pre-recorded biural auditory bleeps at varying and unpredictable rates so as to make it difficult for a participant to effectively count the number of bleeps (Valentine & Sweet, 1999). These researchers observed superior performance of mindfulness meditators on the Wilkins' counting test relative to controls. This study expands on the previous study through illustrating an effect of the amount of meditation experience on sustained attention abilities. Specifically, long-term meditators showed enhanced performance on the Wilkins' test relative to short-term meditators (Valentine & Sweet, 1999). This pattern of improvements in the ability to concentrate following mindfulness intervention has also emerged as a consistent theme in a meta-analysis of the psychological concomitants of mindfulness meditation practices (Ivanovski & Malhi, 2007).

The orienting system is another portal through which mindfulness exerts attentional gains, as illustrated by an enhanced ability to shift the attentional focus. One study compared performance of experienced mindfulness meditators to a control group with no prior mindfulness meditation experience on measures of Stroop interference and the d2-concentration and endurance test (Moore & Malinowski, 2009). The d2-concentration and endurance test is a timed task of selective attention, which requires participants to discriminate and cancel through targets ("d") and visually similar non-targets, in order to estimate individual attention and concentration. Results of the study suggested that attentional performance and cognitive flexibility are

positively related to meditation practice and levels of mindfulness. Importantly, experienced meditators showed advances in cognitive flexibility, a function of attention synonymous with attentional shifting (Moore & Malinowski, 2009).

Another study utilized a more controlled approach to probe the influence of mindfulness on the orienting system through randomization of participants to one of two types of mindfulness training programs (Jha, Krompinger, & Baime, 2007). Relative to a group of concentrative meditators who participated in a mindfulness retreat, individuals naïve to mindfulness who engaged in a MBSR program demonstrated improved orienting post intervention (Jha et al., 2007). Additionally, a sample of experienced mindfulness meditators demonstrated better orienting, operationalized as shorter reaction times, in comparison to an age and gender matched control group on this same skill (van den Hurk, Giommi, Gielen, Speckens, & Barendregt, 2009). The common theme among these studies is a productive relationship between mindfulness and behavioral manifestations of the orienting system of attention.

The final subsystem of attention that has been tied to mindfulness practices is the executive network. One phenotype of engagement of the executive system is attentional focus. When this system is not engaged, mind wandering ensues. In a study that utilized a mindfulness of breathing intervention, behavioral indices of mind-wandering during an attentional task were reduced relative to passive relaxation and reading exercises, suggesting a negative relationship between mindfulness and mind-wandering (Mrazek, Smallwood, & Schooler, 2012). Not only does mindfulness reduce the presence of mind-wandering, it is also tied to enhancements in the efficiency of the executive attentional network. In a study examining the attentional processing of experienced mindfulness meditators relative to controls, meditators showed superior executive attention, as defined by improved error score (van den Hurk et al., 2009). Increases in the

efficiency of the executive attentional network is also associated with the amount of meditation experience, wherein time spent meditating each day has been linked to improvement on an executive control task among mindfulness meditators (Chan & Woollacott, 2007).

Together, these cognitive and behavioral studies demonstrate a beneficial influence of mindfulness practices on three networks of attentional functioning. Of these advantages, it is likely that improvements in the executive network of attention are associated with the early phases of mindfulness training, distinguished by the development of focused attention (Chiesa, Calati, & Serretti, 2011). Additionally, improvements in sustained attention abilities of the alerting attention system likely relate to later phases of mindfulness training, characterized by an open monitoring of internal and external stimuli (Chiesa et al., 2011).

Electrophysiological studies are another valuable tool in studying the effects of mindfulness on attentional processing. As with cognitive and behavioral studies of mindfulness and attention, this category of research supports mindfulness as an advantageous practice for attentional mechanisms. One of the ways in which mindfulness has shown utility in attentional functioning is through enhancement of cerebral areas related to attention following long-term meditation practice (Chiesa & Serretti, 2010). Not only does mindfulness activate attentional regions of the brain, attentional resources become better focused and allocated after mindfulness meditation exposure, as indexed by ERP components related to attention (Moore, Gruber, Derose, & Malinowski, 2012).

Conclusions of a recent meta-analysis of EEG, ERP, and neuroimaging studies surrounding meditation practices support the notion that such traditions augment attentional allocation, and suggest that meditation reflects changes in the anterior cingulate cortex (ACC) and dorsolateral prefrontal areas (Cahn & Polich, 2013). This second conclusion has been

corroborated by other neuroimaging studies, showing an activation of the prefrontal cortex (PFC) and the ACC during mindfulness meditation practice (Chiesa & Serretti, 2010). Additional support for this trend is the association of increased theta activity with level of mindfulness related meditation experience, as frontal theta reflects involvement of attentional networks in the prefrontal neural circuitry, including the ACC (Ivanovski & Malhi, 2007).

Important to the present study, is a finding that increased ACC activity is associated with meditation practice in novices (Tang, Ma, Wang, Fan, Feng, Lu et al., 2007). This result is particularly relevant, as one function that relies primarily on ACC-related neural processing is monitoring performance for conflict and errors (Tang et al., 2007). Provided the connection between ACC activity and error monitoring, the present study aims to determine whether mindfulness, a specific form of meditation practice, will influence error monitoring. A useful tool to measure the neural markers of error is electroencephalography, which can be used to elucidate the influence of mindfulness practice on error monitoring.

Electroencephalography

As previously introduced, electroencephalography (EEG) is a well-suited method to study neural indices of error monitoring. One noteworthy advantage of EEG methodology in the study of mindfulness and cognition is the high temporal resolution of cognitive events EEG affords, given the temporal aspect of mindfulness. To examine the neural effects of mindfulness, the present study will utilize EEG, which records electrical activity from the scalp. Embedded within the electrical chaos that is recorded via EEG are neural responses related to distinct sensory, cognitive, and motor events (Luck, 2005). These neural responses, known as event-related potentials (ERPs), reflect changes in electrocortical activity, and are extracted from EEG data using a simple averaging technique (Ito, Larsen, Smith, & Cacioppo, 1998; Luck, 2005).

Of particular importance to cognitive neuroscience research are time-locked structural features of the ERP identified by the peaks in and spatial distribution of the waveforms in an EEG record, referred to as ERP components. ERP components are understood to reflect one, or more, information-processing operations and are quantified by their amplitude and frequency (Ito et al., 1998). The amplitude of an ERP component is thought to indicate the extent to which an information processing operation is engaged, while the latency of an ERP component is believed to be an index of the rate of processing (Ito et al., 1998). Of particular importance to the present study are the error-related negativity (ERN) and error positivity (Pe), two error-related ERP components that are identified using EEG methodology.

Distinct from ERP components, the EEG also records neuroelectric oscillatory activity with varying frequencies. These neural oscillations are quantified by their frequency and are thought to reflect distinct levels of alertness and arousal states. Similar to ERPs, oscillatory phenomena including alpha, theta, delta, and gamma waves are interwoven with sensory and cognitive functions (Başar et al., 2001). Focal to the present study are changes in the oscillatory activity within the alpha power range of the EEG following error trials, termed error-related alpha suppression (ERAS; Compton, Bissey, & Worby-Selim, 2014). One way to record and measure this novel error-related neural marker is through the use of EEG.

The Error-Related Negativity

EEG is a valuable method for studying executive control, as it allows researchers to examine the neural markers of error monitoring. An enhanced understanding of the relationship between mindfulness and error monitoring will provide insight into how mindfulness influences responses to negative events, which has particular importance for psychological well-being.

Error monitoring concerns the signaling and detection of errors in order to optimize behavior over a vast variety of tasks and situations (Moser, Moran, Schroder, Donnellan, & Yueng, 2013).

A widely recognized neural marker of error monitoring is the error related negativity (ERN), a time-locked ERP component characterized by a negative going-inflection that occurs at or shortly before execution of an erroneous response during a cognitive task (Kappenman & Luck, 2012). The ERN signifies an internal recognition of error commission, as it occurs in the absence of external negative feedback (Teper & Inzlicht, 2014). The ERN is observed as a focal negativity maximal over midline fronto-central recording sites on the scalp and peaks approximately 100 ms after an error has been elicited (Kappenman & Luck, 2012).

The ERN occurs on error trials in a wide range of speeded-response tasks involving stimuli and responses of various perceptual modalities. One such speeded-response task is the Stroop test, wherein individuals are required to indicate the font color of a word presented to them on a computer screen. When EEG is used to measure the brain's responses to correct and error trials on the Stroop, the EEG record will show a negative-going peak when a participant makes an incorrect response, indicating the presence of the ERN.

The ERN is generated in the anterior cingulate cortex (ACC), a region of the medial prefrontal cortex related to cognitive control processes, which allow the brain to adapt to evolving task demands and environmental circumstances (Kappenman & Luck, 2012; Hajak, 2012). Cognitive control functions involve processes that detect when control is necessary, such as when performance breaks down, and processes that employ control through changes in attentional focus. Since an error acts as a salient marker to the brain that performance has broken down, the ERN is understood to reflect a process involved in evaluating the need for or implementing cognitive control (Kappenman & Luck, 2012). Specifically, due to its relationship

to incorrect responses, the ERN is thought to signal the early activity of a general error-processing system (Hajak, 2012).

While several theories regarding the function of the ERN have been proposed, the reinforcement-learning theory and the conflict-monitoring theories have gained the most support (Kappenman & Luck, 2012). Though these theories diverge in some respects, both theories posit that the magnitude of the ERN is directly related to performance measures and is utilized to improve subsequent behavior (Hajak, 2012). In support of this conceptualization of the ERN, is a finding that individual differences in the ERN predicted post-error accuracy on a behavioral task (Carp & Compton, 2009). Specifically, higher ERN difference scores, indicating a more negative, or increased, amplitude of the ERN predicted higher post-error accuracy scores on the Stroop test. These results suggest that a larger ERN peak is associated with improved performance following errors. Relatedly, one study found that an enhanced ERN response to errors predicted better academic performance in college students, measured by official student transcripts (Hirsch & Inzlicht, 2009). A heightened ERN response has also predicted improvement on behavioral measures of self-efficacy and improved accuracy following error trials (Themanson, Pontifex, Hillman, & McAuley, 2011; Carp & Compton, 2009).

Importantly, other behavioral outcomes including emotion and stress regulation appear to be related to individual differences in the ERN. In two studies, individual differences in neural and behavioral responses to performance mistakes predicted daily accounts of mood and coping (Compton, Arnstein, Freedman, Dainer-Best, Liss & Robinson, 2011; Compton, Robinson, Ode, Quandt, Fineman, & Carp, 2008). Specifically, participants with effective error detection, as indexed by the ERN, and adaptive post-error behavioral changes tended to show less self-reported negative affect and more task-focused coping behaviors in response to daily stressors

over a 2-week period. These results suggest that an improved or increased response to errors reflected by the ERN enables effective emotion and stress regulation.

Additional evidence to support the relationship between the ERN and adaptive stress responses comes from a recent study by Compton, Hofheimer, and Kaznika (2013a), wherein greater differentiation of correct and error trials by the ERN predicted less task-related cortisol increase. Provided that increases in cortisol signal an engagement of the stress response, these results imply that individuals with pronounced ERNs exhibit superior stress regulation during cognitive tasks. Together, studies on this neural marker of error-monitoring demonstrate that it is related to improved emotion and stress regulation. While other findings reporting a positive association between anxiety and ERN amplitude contradict this conclusion, these studies typically employ clinical populations. Given the heritability and stability of the ERN, it is possible that a heightened ERN in clinical samples may be an inherent trait, and relate less to the ability to effectively manage emotions and stress (see Hajak, 2012 and Moser et al., 2013 for a more complete review).

Taken together, these findings on the ERN suggest that an enhanced ERN is a part of an adaptive cognitive control system, as it predicts behavioral improvements in the academic setting, self-efficacy, emotion regulation, and stress management. The present study seeks to provide additional evidence to support the idea that the ERN is an adaptive phenomenon through examining the effect of mindfulness practices on ERN amplitude. Since mindfulness is known to be beneficial for physical and mental well-being, a positive relationship between mindfulness and an enhanced ERN would further support the hypothesis that the ERN is an adaptive error response.

The ERN and Mindfulness

Provided that meditative practices typically require focusing on internal sensations, it follows that mindfulness may result in enhanced sensitivity to internal stimuli. Indeed, mindfulness is characterized by enhanced visceral and emotional awareness, which lends support to the suggestion that mindfulness results in increased attention to internal stimuli (Teper & Inzlicht, 2014). Since errors are internally generated, it is likely that mindfulness would amplify the neural reaction associated with them. Additionally, the ERN may be considered a form of internal feedback, as it is produced in response to an individual's recognition of their error, not in response to external feedback (Teper & Inzlicht, 2013). This rationale, as well as evidence supporting the ERN as an adaptive response to error commission, suggests that mindfulness will enhance the ERN response.

In support of this proposition is a finding from a recent study by Teper and Inzlicht (2013) on the influences of mindfulness meditation practice on executive control. In particular, the study examined how the effect of mindfulness meditation on executive control manifests in the brain, as indexed by neural correlates of performance monitoring. Participants were experienced meditators with at least one year of meditation experience and non-meditators (control) with no prior meditation experience. In the study, participants completed the Stroop test as a measure of executive control while their neuroelectric activity was recorded via EEG. Meditators exhibited greater executive control, illustrated by fewer errors on the Stroop and higher ERN amplitude, suggesting that meditators react quickly to their errors. Interestingly, ERN amplitude was correlated with mindfulness acceptance, while the present moment attention facet of mindfulness did not correlate significantly with the ERN. This result suggests that individuals who are more accepting of their sensory, emotional, and mental experiences display

higher amplitude ERNs and that the executive control benefits of meditation are likely related to affect, rather than attention. It is also conceivable that a heightened ERN reflects greater awareness of errors, as these results do not completely rule out this possibility.

Other studies have failed to support this pattern of results. In one study, researchers utilized a brief mindfulness meditation intervention administered via CD audio exercise (Larson, Steffen, and Primosch, 2013). After exposure to a mindfulness or control exercise, participants completed a modified Eriksen flanker task while EEG and behavioral data were recorded. Though individuals in the mindfulness condition exhibited greater ERN amplitudes than control participants in response to performance errors, this between-group difference did not reach statistical significance. Due to the lack of significant results regarding mindfulness and the ERN, these researchers proposed that state changes in mindfulness might not be powerful enough to elicit an effect on ERN amplitude.

Provided the mixed results from studies examining mindfulness and the ERN, as well as the dearth of studies relating these concepts, there clearly exists a research gap that signals a need for additional work on mindfulness and the ERN. The present study aims to address this aperture through close replication of the Larson et al. (2013) study. The results of the present study will test whether a brief mindfulness intervention is enough to observe changes in the neural response to errors, as indexed by the ERN. This study improves upon Larson et al. (2013) study in that it will utilize already mindful individuals (as described in the methods section), where an effect of a brief mindfulness intervention may be stronger and more likely to reveal neural changes in error reactivity.

Error Positivity

In studying the influence of mindfulness on error monitoring, it is important to examine the error positivity (Pe), another well-established error-related ERP component. Error positivity (Pe) is an ERP characterized by a positivity that occurs during the response-locked error-trial waveform following the ERN (Kappenman & Luck, 2012). Pe is observed most prominently over the centro-parietal recording sites on the scalp and has peak amplitude between 200 and 400 ms after error commission (Kappenman & Luck, 2012). Though different theories regarding the functional significance of the Pe have been postulated, most research supports the notion of Pe as a reflection of error awareness and motivational salience.

The error awareness hypothesis posits that the Pe reflects conscious recognition of error commission. In support of the notion that Pe is a manifestation of error awareness are findings from several studies that Pe amplitude covaries with the degree of awareness of an error (Overbeek, Nieuwenhuis, and Ridderinkhof, 2005).

Of particular interest to the present study is the conceptualization of Pe as a reflection of the motivational salience of an error. This hypothesis was ignited through recognition of the similarities between Pe and P3, an ERP component elicited by motivationally significant stimulus events, including task-relevant, novel stimuli (Overbeek et al., 2005). Comparisons of the Pe and P3 show that these two waves are alike in terms of timing, morphology, scalp topography, and significance (Ridderinkhof, Ramautar, and Wijnen, 2009). These similarities led to the notion that Pe may reflect a P3b peak associated with the motivational significance of an error. Specifically, these two ERPs may also be functionally similar in the sense that Pe reflects the motivational significance of a salient performance error, analogous to the P3 as an index of the motivational significance of a rare target stimulus. This suggestion is directly supported by

research showing a larger Pe in response to more salient errors (Overbeek et al., 2005).

Additionally, intentional errors, which presumably are not experienced as very salient, elicit a smaller Pe than genuine errors (Overbeek et al., 2005). One study examined the functional significance of the Pe using a target-to-target interval (TTI) manipulation designed expressly to tap into the motivational salience processing proposed to be reflected by the Pe (Ridderinkhof et al., 2009). These researchers observed a correlation between Pe amplitude and the parametric effect of TTI on P3 amplitude, suggesting that Pe and P3 reflect similar neurocognitive processes involved in the conscious processing of motivationally significant events. Given the support for the Pe as a reflection of error salience, it is plausible that a tool for relieving mental and physical suffering such as mindfulness may influence Pe in such a way that error salience is attenuated.

Error Positivity and Mindfulness

The relationship between error positivity and mindfulness was first examined by Teper and Inzlicht (2013) in a study examining the influence of meditation practice on executive control. In particular, these researchers were interested in error-related manifestations of executive control and thus measured the ERN and Pe, two neural correlates of performance monitoring. Their sample included novice and experienced meditators who engaged in a Stroop test while electrophysiological and behavioral data were collected. Results of this study did not indicate a significant difference between meditators and non-meditators on Pe amplitude. However, control participants appeared to show more positive Pe amplitudes than did the mindfulness meditator participants. As mentioned previously, this study did observe a significant effect of condition on ERN amplitudes. Taken together, these findings suggest that while meditators react swiftly to their errors as reflected by higher ERN amplitude, they are also quick to let go of any reaction associated with them. This explanation is consistent with the acceptance

facet of mindfulness, though results regarding the influence of mindfulness meditation on Pe did not reach significance.

While mindfulness meditation experience did not significantly influence Pe amplitude, findings of a study that utilized a brief mindfulness meditation intervention suggest that mindfulness exposure can influence the error positivity (Larson et al., 2013). In the study, participants were randomly assigned to a mindfulness or control condition, involving a mindfulness of breathing exercise or audio tracks involving information on environmental awareness and ethical behaviors, respectively. After participation in one of the two forms of the intervention, participants completed a modified Eriksen flanker task while electrophysiological and behavioral data were collected. Results of the study revealed a significant between group difference on error-trial Pe amplitude, with significantly depressed amplitude of the Pe in participants in the mindfulness condition relative to control participants. Possible interpretations of this finding propose that individuals who complete a brief mindfulness intervention become less aware of their errors, or find them less motivationally salient, based on theories regarding the functional significance of the Pe. Importantly, this study was the first to show that a brief mindfulness intervention has the capacity to decrease the amplitude of the Pe.

Though the present study closely models the methodology of the Larson et al. (2013) study, it will improve upon this approach through implementation of a cleaner intervention. By balancing groups based on trait mindfulness (as will be explained later in the proposal), the present study will be able to determine if the intervention itself has a significant effect on error positivity, or whether this effect is a result of pre-existing levels of mindfulness. The aim of the main study is to replicate findings by Larson et al., (2013) and depict a stronger relationship between Pe and mindfulness, provided by baseline measurements of trait mindfulness. Reducing

error salience or influence may reflect a more adaptive response to errors and to negative life events more broadly. Specifically, if Pe amplitude were reduced following the mindfulness induction, this finding would lend additional support to the beneficial influence of mindfulness on executive control and perhaps well-being.

Error related alpha suppression

A final error-related phenomenon connected to error monitoring that has not yet been studied in relation to mindfulness meditation is error related alpha suppression (ERAS). Recently, researchers observed a trend wherein oscillatory activity in the alpha power range increased and subsequently decreased following correct trials on a behavioral task (Carp & Compton, 2009). However, this trend was absent following errors, which elicited significantly less alpha power than correct trials. This novel error-related neural phenomenon, termed error-related alpha suppression (ERAS), reflects changes in alpha oscillatory activity recorded via EEG. Alpha waves are commonly present during relaxed or mentally drowsy states, and increases in mental activity or alertness lead to a relative decrease in the power within the alpha frequency band (Carp & Compton, 2009). Provided that alpha power is inversely related to mental activation, suppression of alpha power reflects an increase in mental activation, or increased external direction of attention, and is considered an arousal/alerting response to errors (Compton, Bissey, & Worby-Selim, 2014). Particularly, this pattern of alpha activity indicates higher cortical arousal after error commission, in contrast to transient mental disengagement following correct responses (Carp & Compton, 2009). ERAS occurs within the intertrial interval between a participant's response and the onset of the next stimulus in a series, and is maximal from 200 to 800 ms post-response (Compton et al., 2014). Though ERAS is widely distributed throughout the scalp, it is most prominent at posterior sites (Compton et al., 2014).

While ERAS is fairly recent discovery, much of the research on this error-related neural pattern suggests that it may be related to maladaptive self-regulatory outcomes in performance and stress-reactivity. In a pioneering study on ERAS, researchers found that post-error alpha power was a predictor of individual differences in post-error slowing, wherein individuals with greater alpha suppression exhibited increased post-error slowing (Carp & Compton, 2009). Though individual differences in alpha power were related to post-error changes in speed, they were not related to post-error changes in accuracy. These results indicate that individuals with enhanced ERAS tend to slow down after they commit an error, though this lag does not improve performance. Instead, this response latency may represent performance inefficiency in individuals with higher levels of alpha suppression.

Another study by Compton, Hofheimer, and Kazinka (2013a) provided more concrete evidence in support of ERAS as a maladaptive error response. These researchers examined the relationship between error-related signals of cognitive control and cortisol reactivity while participants completed a Stroop task. Importantly, increased ERAS to errors on this task predicted greater cortisol increase during the task. On the other hand, the ERN showed an opposite pattern of relationship with cortisol, suggesting that these two error-related phenomena reflect functionally different responses to errors. As cortisol is a hormone tied with stress reactivity, these results imply that enhanced ERAS may reflect error-related arousal that is maladjusted and begets less successful stress regulation. Building upon the view of ERAS as a maladaptive response to errors are findings that ERAS is correlated with increased negative affect, less positive affect, more state anxiety, and additional blame-focused coping (Compton, Hofheimer, Kazinka, Levinson, & Zheutlin, 2013b; Compton, Goodman, Worby-Selim,

unpublished). Taken together, these findings indicate that an enhanced ERAS response is maladaptive and relates to an inability to effectively regulate stress.

However, other research suggests that ERAS may actually play an adaptive role following lapses in attention. Results of a series of studies on the ERAS indicated that adaptation following attentional lapses, as evidenced by posterror slowing, on a sustained attention Simon task condition involved posterior alpha power suppression (van Driel, Ridderinkhof, and Cohen, 2012). These results contradict previous findings, as task improvement was related to stronger error-related suppression of alpha power.

While literature on ERAS has not come to a clear conclusion on whether this error-related trend reflects a maladaptive or adaptive process, most research suggests that an enhanced ERAS response is not adaptive, given the association of ERAS with typically negative phenomena. The present study will be the first to examine the influence of mindfulness on ERAS, and aims to provide further evidence to either support or refute ERAS as a maladaptive response. Since mindfulness is typically associated with adaptive and positive outcomes, if mindfulness alleviates suppression of alpha following error trials, this result will favor the notion of ERAS as a maladaptive process. However, if mindfulness enhances the ERAS response, previous literature supporting ERAS as a maladaptive response may need to be reinterpreted.

The present study will also improve upon previous work related to ERAS through implementation of an experimental manipulation to examine the influence of mindfulness on ERAS. Most studies to date on ERAS are correlational in nature and thus no causal conclusions can be drawn. However, the present study will employ randomization to a mindfulness or control condition in order to compose causal conclusions regarding mindfulness and error-related alpha suppression.

The Present Study

Mindfulness has been robustly linked to improvements in psychological well-being and physical and mental health, including clinical implementation of mindfulness interventions to effectively treat various mood and anxiety disorders. Due to the beneficial outcomes of mindfulness on mental health, research on the mechanisms underlying these influences has boomed. One such mechanism that has been studied in relation to mindfulness meditation practices is cognitive control, which allows the brain to respond and adapt to evolving task and environmental demands. Research espousing the influence of mindfulness meditation on cognitive control is growing, with findings supporting a positive relationship of mindfulness with emotion regulation and attention.

In order to expand on the existing literature on the mechanisms wherein mindfulness exerts its benefits, the present study will investigate how mindfulness influences performance monitoring. Through examination of the impact of mindfulness on the way in which the brain responds to performance errors, this study will provide insight as to how mindfulness affects responses to negative life events. In particular, mindfulness meditation may reduce the adverse effects of errors, a specific type of negative life event, thereby influencing mental health and well-being. This study will determine whether mindfulness has a positive influence on performance monitoring by examining error-related neural markers and behavioral performance on a task related to executive control after implementation of a brief mindfulness induction. Provided the robust evidence that supports the ERN, Pe, and ERAS as correlates of performance monitoring, the present study will use these phenomenon to reflect neural markers of error.

Mindfulness is characterized by increased momentary awareness of errors, suggesting that the error related negativity (ERN) might be increased following a mindfulness induction, as

this neural marker occurs shortly after error commission and before onset of the Pe and ERAS. Indeed, in one study examining the influence of mindfulness meditation experience on cognitive control, experienced meditators exhibited enhanced ERN amplitudes to error trials on a Stroop task compared to a control group with no prior meditation experience (Teper & Inzlicht, 2013). Other literature on the ERN suggests that an enhanced ERN is a component of an adaptive cognitive control system, as it predicts improvements in academic performance, self-efficacy, emotion regulation, and stress management (Hirsch & Inzlicht, 2009; Themanson et al., 2011; Teper & Inzlicht, 2013; Compton et al., 2013a). Provided the robust evidence supporting the benefits of mindfulness on physical and mental well-being, an enhanced ERN following a mindfulness induction would coincide with current research on these concepts and further support the notion of the ERN as an adaptive error response.

Another error-related neural marker that will be analyzed in this study in relation to mindfulness is error positivity (Pe). Given the support for the Pe as a reflection of the importance of errors, it is plausible that a tool for relieving mental suffering such as mindfulness may influence Pe in such a way that error salience is attenuated. Thus, we predict that individuals in the mindfulness group will place less importance on their errors, resulting in decreased Pe amplitudes for this condition. This suggestion is in line with results of a study on mindfulness and cognitive control, wherein a brief mindfulness intervention was associated with decreased amplitude of Pe (Larson et al., 2013).

The third neural correlate of error monitoring that will be examined in the study is error-related alpha suppression (ERAS). While literature on ERAS has not come to a clear conclusion on whether this error-related trend reflects a maladaptive or adaptive process, most research suggests that an enhanced ERAS response is not adaptive, given the association of ERAS with

typically negative phenomena. From this notion of ERAS, it is hypothesized that mindfulness, a tool for enhancing positive outcomes and processes, will reduce the presence of ERAS.

Additionally, the placement of the ERAS late in the time sequence of error response suggests that ERAS may reflect an elaboration or rumination process that mindfulness is known to decrease. While the ERN occurs earlier in the stream of error processing and signals an awareness of errors that is heightened through mindfulness practice, the ERAS reflects a temporally distinct neurocognitive process that will be attenuated following mindfulness practice. Mindfulness is also thought to decrease arousal to negative events. Provided the ERAS as an arousal response to errors, it follows that mindfulness will diminish suppression of alpha oscillatory activity. Specifically, individuals exposed to a mindfulness induction will exhibit less ERAS relative to a control condition.

Although behavioral outcomes of mindfulness are not central to the present study, both accuracy and efficiency data on a behavioral task will be collected and compared between the mindfulness and control conditions. In previous research, novice meditators showed improved performance and greater efficiency compared to a control condition on the Stroop task after engaging in meditation exercises (Wenk-Sormaz, 2005). Based on these findings, improved performance, as indexed by increased accuracy and efficiency, are expected for the mindfulness group relative to a control condition.

Hypotheses. The expected results of the present study, arising from the reasoning outlined above, are as follows:

EEG/ERP Predictions:

H1: Individuals exposed to a mindfulness induction will exhibit a larger (more negative) ERN peak than individuals in a control condition.

H2: Individuals in the mindfulness meditation induction will show an attenuated Pe amplitude compared to control participants.

H3: Individuals exposed to a mindfulness meditation induction will have reduced ERAS compared to individuals in a control group.

Behavioral Predictions:

H4: Participants in the mindfulness condition will show improved accuracy on the Stroop test, relative to control participants.

H5: Participants in the mindfulness condition will have reduced reaction times on the Stroop test, relative to control participants.

Methods

Participants

Participants were undergraduate students ($n=37$, 10 male, 27 female) recruited from Haverford College. The thirty-seven participants in the study were divided across conditions, resulting in two conditions, experimental (mindfulness) with 18 participants, and control with 19 participants. Data analysis was conducted on thirty-three of the thirty-seven participants due to the necessary exclusion of four participants. Of the four participants removed from analysis, three participants were removed from the mindfulness condition and one was removed from the control condition, occasioning 15 (6 male, 9 female) and 18 (4 male, 14 female) participants in each of these conditions respectively. The participants in the mindfulness group were removed due to exceedingly high error rate, poor quality from two critical recording sites, and technical difficulties. The one participant excluded from the control condition had too high of an error rate to be used for further analysis.

Before engaging in the main experiment, participants completed a brief pre-screening questionnaire to balance conditions based on trait mindfulness. Trait mindfulness was assessed using the awareness scale of the 39-item Five Facet Mindfulness Questionnaire (FFMQ) (Baer, Smith, Lykins, Button, Krietemeyer, Sauer, et al., 2008). The awareness factor of the FFMQ was chosen as a focus because the concept of awareness is most relevant to the attention and cognitive control processes examined in the present study. For purposes of this study, the other mindfulness factors were not considered in our data set, but they may be relevant for exploration in future studies. The pre-screening survey also included the 16-item Penn State Worry Questionnaire (PSWQ), designed to assess the generality, excessiveness, and uncontrollability of participants' experience of pathological worry (Meyer, Miller, Metzger, & Borkovec, 1990). Additionally, the pre-screening questionnaire collected participants' basic demographic information, which was used in order to balance groups on gender. According to statistical analysis, groups did not differ based on gender and ANOVA tests incorporating gender revealed no significant effects of gender on physiological or individual differences measures; therefore, gender is not considered further. Results of this pre-screening were also used to assign participants to either an experimental condition or control condition.

Design

The study includes one independent variable, induction condition, with two between-subject conditions: control and mindfulness. Participants in the control condition listened to instruction on awareness and ethics, whereas individuals in the mindfulness condition engaged in a mindfulness of breathing exercise. The average ERN and Pe amplitudes of each group were calculated for correct and error trials to determine the differences of these two error-related ERP components depending on condition. Additionally, alpha power following correct and error trials

was measured for each group in order to assess the influence of condition on ERAS. To ascertain the impact of mindfulness on behavior, response accuracy and response time to each stimulus was calculated for congruent, incongruent, and neutral trials on the Stroop test. Specifically, these measurements enabled evaluation of Stroop effect interference, performance accuracy, and efficiency between conditions.

Procedure

The procedure of the present study was identical for mindfulness and control conditions, with the exception of the form of induction each condition experienced. Upon entry into the lab, participants received and completed an informed consent document, indicating their willingness to partake in the study. Participants were then fitted with the electrode EEG cap to record their neuroelectric activity while they completed a behavioral task later in the session. Subsequently, participants engaged in a mindfulness meditation exercise or a control listening exercise (described below). Immediately following the mindfulness or control exercise, participants completed the 20-item state anxiety scale of the State Trait Anxiety Inventory (STAI) to measure the intensity of anxiety experienced as an emotional state post-intervention (Spielberger, 2010). This self-report questionnaire served as a manipulation check of the mindfulness intervention and its ability to effectively influence stress levels. After completion of this survey, participants completed the Stroop test while EEG and behavioral data were recorded. Following the Stroop test, participants completed a brief survey assessing prior familiarity and experience with mindfulness meditation techniques on a scale of 1 to 10, 1 denoting “never heard of mindfulness meditation previously” and 10 indicating “prior experience engaging in mindfulness meditation practices”. Participants were provided with \$20 for participation.

Mindfulness and Control Exercises

Mindfulness and control condition exercises were chosen from Jon Kabat-Zinn's *Mindfulness for Beginners* 2-disc CD set. Individuals in the mindfulness condition participated in a *Mindfulness of Breathing* (time=14:33) audio exercise, focused on attending to their breath and being mindful in the moment. Control participants listened to two instructional CD sections on mindfulness, including *Awareness, A Sixth Sense* (time=7:41) and *An Ethical Foundation* (time=6:38). These clips included educational information on environmental awareness and ethical behavior, though they did not involve any mindfulness meditation (MM) practice. All participants heard the same voice from the same set of CDs and for the same amount of time. The important distinction between conditions was that the mindfulness group engaged in a mindfulness of breathing exercise, while the control condition heard educational CD tracks with no active participation in a MM exercise. This particular form of mindfulness induction was implemented in the present study given its success as a mindfulness intervention in a previous study on mindfulness and performance monitoring (Larson et al., 2013).

Behavioral Task

Participants completed a six-option Stroop test modeled after Compton, Hofheimer, & Kazinka (2013a), as a measure of executive control. Though the quintessential Stroop test typically involves two choices, a six choice task was used in an effort to increase the probability of errors and Stroop interference. The Stroop test included a series of stimulus color words, with each word presented in a color that either matches (congruent trial) or does not match (incongruent trial) the semantic meaning of the word. This test also incorporated a series of stimulus words unrelated to color, such as "dog", which comprised the neutral trials in the test. Participants were instructed to indicate the font color of each word presented to them by means

of a keystroke response corresponding to a specific color of the rainbow. The six possible responses included red, orange, yellow, green, blue and purple, which flowed from left to right across the keyboard. Responses were elicited by the three first fingers of each hand on a keyboard, with corresponding keys mapped to one of the six color options.

Each trial in the test involved presentation of a stimulus word against a black background for 150-ms, followed by a blank screen shown until the participant made a response, or for a duration of 2000-ms. Once a response was elicited, a blank screen was displayed for a 1,280-ms intertrial interval (ITI) before onset of the next trial. Participants completed 24 practice trials, to which they received explicit accuracy feedback to ensure they understood the instructions and the stimulus-response keystroke mapping. However, no such explicit feedback was provided on the remainder of the experimental trials. Upon completion of the practice trial set, participants finished eight experimental trial blocks with 90 trials per block, creating a sum total of 720 experimental trials per participant.

Electrophysiological Recording and Processing

Electrodes were applied using an elastic cap (Quik-Caps) embedded with sintered Ag/AgCl electrodes. Data was continuously recorded from four midline scalp sites (Fz, FCz, Cz, and Pz), as well as three pairs of lateral sites (F3/4, C3/4, and P3/4). Electrical signals were amplified using a NuAmps amplifier monitored by Neuroscan software, with a sampling rate of 1000 Hz and a bandpass of 0.1-40 Hz (-3 dB). The right mastoid site was used as an online data reference point and data was digitally re-referenced offline to the average of left and right mastoid sites. Eye movements were monitored by electrodes placed above and below the left eye and at the outer canthus of each eye. Recordings from these facial sites were used to compute bipolar horizontal and vertical electrooculogram channels offline.

Artifacts were attended to offline in a series of steps. Initially, the EEG record was visually examined for portions with large non-blink artifacts and these sections were manually excluded. Next, NeuroScan software's regression-based algorithm for ocular artifact rejection was employed to decrease the influence of blinks on EEG data. Any remaining artifacts were identified using a ± 150 - μV threshold and the epochs corresponding to these artifacts were excluded.

Data processing to extract the ERN, Pe, and ERAS involved the creation of epochs surrounding each response marker (button press), indexed by Time 0. For the ERN and Pe, these epochs began 200 ms before the response and extended to 600 ms post-response. Epochs were baseline-corrected, with the baseline defined as voltages in an interval ranging from 200 to 100 ms pre-response. These epochs were separately averaged for correct and error trials in order to create an average waveform for each of these forms of response. The most negative value between -50 and 100 ms surrounding a button press response was used to define the ERN. The Pe was defined as the mean amplitude between 100 and 300 ms post-response. Analysis of the ERN and Pe data focused on the midline sites (Fz, FCz, Cz, and Pz) where these phenomena are reliably observed.

In addressing alpha power changes following error commission, power spectra were computed for five 256-ms time periods initiated at the time of response and continued throughout the ITI. The fast Fourier transform and a cosine windowing method was utilized to obtain power spectra for each time period. This technique yielded time frequency representations of the ITI with a temporal resolution of 256 ms and a frequency resolution of 4 Hz. Spectra for each time window was then averaged separately based on trial type (i.e., error vs. correct). Statistical analyses were conducted using log-transformed mean power values in the 10- to 14-Hz

frequency band. Analysis of ERAS focused on midline sites (Fz, Cz, Pz) and lateral sites (F3, F4, C3, C4, P3, P4) provided the broad distribution of ERAS on the scalp.

Results

A significance level of $p < .05$ was used as a cutoff to determine meaningful relationships between the included factors in the analysis.

Individual Differences (Self-Report) Data

In order to determine whether condition differed with respect to several individual difference measures, an independent samples t-test was performed to compare mindfulness experience level, and STAI and PSWQ scores in the mindfulness and control conditions. There was no significant difference between condition on STAI score, $t(31) = -.761, p = .453$. This result indicates that participants in the experimental condition were no less anxious than those in the control condition following the mindfulness induction, suggesting a lack of efficacy of the mindfulness manipulation. However, there was significant difference between conditions with respect to PSWQ scores at the time of screening, such that participants in the mindfulness condition had lower levels of anxiety ($M = 44.3, SD = 11.0$) than those in the control condition ($M = 54.4, SD = 10.1$), $t(31) = -2.77, p < .01$. This significant difference in PSWQ scores across condition introduces a potential confound of worry into all subsequent analyses including condition and PSWQ scores. On the other hand, there was no significant difference in mindfulness experience between conditions, thereby eliminating the possibility of this variable to confound further analysis; $t(31) = .566, p = .575$.

To assess the relationship among the individual differences included in the study, a correlation analysis was performed including STAI and PSWQ scores, as well as mindfulness experience and awareness levels. Results indicated a significant positive correlation between

PSWQ and STAI scores, showing that participants who reported worrying more at the time of the pre-screening were also more likely to be anxious during the experimental session, $r = .668, p < .001$. State anxiety was also significantly correlated with awareness level, such that those with higher STAI scores had lower levels of awareness, $r = -.378, p = .03$. Additionally, there was a marginal negative correlation between STAI score and mindfulness experience level, $r = -.341, p = .052$. The negative correlation between these two variables demonstrates that individuals who have more experience with mindfulness are less anxious. The negative associations of state anxiety with awareness, a central aspect of mindfulness, and mindfulness experience are in line with empirical data supporting mindfulness as a mechanism to reduce stress (Hofmann et al., 2010). Interestingly, mindfulness experience level was completely uncorrelated with awareness, thereby questioning whether these two constructs were assessing the same aspect of mindfulness, $r = .001, p = .996$.

Performance Data

Accuracy, defined as proportion correct, on the Stroop test was assessed using a 2 x 3 mixed factorial ANOVA, with condition (mindfulness vs. control) as a between-subjects factor, and trial type (congruent, incongruent, neutral) as a within-subjects factor. There was a significant main effect of trial type on accuracy, $F(2, 62) = 14.5, p < .001$. Bonferroni corrected post-hoc analysis indicated that accuracy was significantly lower ($p < .05$) for incongruent trials ($M = .887, SEM = .020$) than for congruent ($M = .916, SEM = .020$) and neutral trials ($M = .919, SEM = .019$), though accuracy on congruent and neutral trials did not differ significantly. These results confirm the hypothesized effect of Stroop interference. However, there was no effect of condition on accuracy on the Stroop test, $F(1, 31) = .032, p = .858$, suggesting that mindfulness induction did not affect overall performance on the Stroop test. Results of this ANOVA also

indicated no significant interaction between trial type and condition, showing that the effects of congruency on accuracy were similar across condition, $F(2, 62) = 1.57, p = .215$.

In order to assess whether trait mindfulness levels had an influence on accuracy on the Stroop test, a 2 x 3 mixed factorial ANOVA was employed with group as a between-subjects factor, trial type as a within-subjects factor, and awareness (used as an index of trait mindfulness) as a co-variate. There was no significant main effect of awareness on accuracy, $F(1, 30) = 1.68, p = .205$. Additionally, there was no significant interaction between accuracy and trial type, $F < 1$. Together, these results indicate that inherent mindfulness levels did not influence Stroop performance.

Reaction time on the Stroop test was examined through a 2 x 3 mixed ANOVA, with group (mindfulness vs. control) as a between-subjects factor, and trial type (congruent, incongruent, neutral) as a within-subjects factor. From this ANOVA, a significant main effect of trial type on reaction time was observed, $F(2, 62) = 111.3, p < .001$. Bonferroni corrected post-hoc analysis revealed that reaction time for incongruent trials ($M = 698$ ms, $SEM = 24.2$) was significantly longer ($p < .05$) than for congruent ($M = 603$ ms, $SEM = 20.5$) and neutral ($M = 595$ ms, $SEM = 20.5$) trial types; however, reaction time on congruent and neutral trials did not significantly differ. These reaction times confirm the predicted Stroop interference effect wherein participants show slower response times for incongruent trials than for congruent and neutral trials. However, there was no significant effect of condition on response time on the Stroop test, indicating that the conditions did not differ with respect to response latency, $F < 1$. There was also no significant interaction between trial type and condition, suggesting that the Stroop interference effect was similar across condition, $F < 1$.

To address the possibility that trait mindfulness effects reaction time on the Stroop, a 2 x 3 mixed ANOVA, with group as a between-subjects factor, and trial type as a within-subjects factor, and awareness as a co-variate was performed. Results of this ANOVA indicated no significant effect of awareness on reaction time, suggesting that trait mindfulness does not impact response latency on the Stroop, $F < 1$.

Together, the accuracy and response time data demonstrate typical Stroop effects and indicate that neither accuracy nor response time were influenced by trait mindfulness or the mindfulness induction.

ERP Data

Error-Related Negativity (ERN)

The ERN was defined as the most negative going peak between -50 and 100 ms surrounding a button press response. ERN data was analyzed using a 2 x 2 x 4 mixed factorial ANOVA, including accuracy (error vs. correct) and electrode site (Fz, FCz, Cz, Pz) as within-subjects factors, and condition (mindfulness vs. control) as a between-subjects factor. Results of this analysis showed a main effect of accuracy on ERN peak amplitude, such that ERN amplitudes were significantly higher following error trials ($M = -4.98 \mu\text{V}$, $SEM = .437$) relative to correct trials ($M = -2.68 \mu\text{V}$, $SEM = .267$), $F(1, 31) = 27.7$, $p < .001$. This result confirms the presence of the ERN during the Stroop test and lends support to the notion of the ERN as an error-related ERP component. The group averaged ERN waveform for correct and error trials can be found in Figure 1.

In order to test the influence of the mindfulness induction on ERN amplitude, the effect of condition was analyzed. There was no significant main effect of condition on ERN amplitudes, $F(1, 31) = 2.19$, $p = .149$. Furthermore, there was no significant interaction between

accuracy and condition on ERN peak amplitudes, $F < 1$. Together, these findings suggest that ERN amplitude was not affected by condition.

To assess the influence of trait mindfulness on ERN amplitude, an awareness factor (used as an index of trait mindfulness) was introduced as a co-variate into the previously described $2 \times 2 \times 4$ mixed ANOVA. Results of this analysis indicated a significant three-way interaction between accuracy, site, and awareness on ERN amplitude, $F(3, 90) = 5.02, p < .03$. Due to this significant interaction, a simple effects analysis was conducted for each recording site to determine the particular site at which the significant interaction between accuracy and awareness occurred. Simple effects analyses showed that the three-way interaction between accuracy, site, and awareness was driven by effects at the Pz recording site (at Pz accuracy \times awareness, $F(1, 30) = 9.9, p < .005$). The two-way interaction between accuracy and awareness was not significant at Fz, FCz, and Cz sites. In order to ascertain the relationship between awareness and ERN amplitude at the Pz site, a simple, bivariate correlation analysis was performed employing these two variables. ERN amplitude at the Pz site was calculated using a difference score of ERN amplitude following correct trials minus ERN amplitude following error trials. This correlation revealed a significant negative correlation between the ERN at the Pz site and awareness, such that the ERN was larger in participants with lower awareness levels, $r = -.503, p < .005$.

To determine the influence of state anxiety on the ERN, a $2 \times 2 \times 4$ mixed factorial ANOVA was performed using accuracy and site as within subjects variables, condition as a between subjects variable, and STAI score as a co-variate. There was a significant interaction between accuracy and STAI score, $F(1, 30) = 5.01, p < .05$. In an effort to examine the direction of the relationship between state anxiety and the ERN, a correlation analysis between STAI score and ERN difference score (correct minus error amplitude) was implemented. There was a

significant positive interaction between STAI score and ERN difference score, indicating that individuals with high state anxiety also have a heightened ERN in response to their errors, $r = .375, p < .05$.

In order to test the influence of previous mindfulness experience on the ERN, a similar 2 x 2 x 4 mixed factorial ANOVA was employed with mindfulness experience level as a co-variable, instead of STAI score. Results of this ANOVA indicated a significant main effect of mindfulness experience level, $F(1, 30) = 8.87, p = .006$. There was also a significant interaction between mindfulness experience level and accuracy, $F(1, 30) = 5.56, p < .03$, and a significant three-way interaction between accuracy, site, and mindfulness experience level, $F(3, 90) = 4.40, p < .03$. Given the quantity of significant ANOVA results connecting mindfulness experience level to the ERN, a correlation analysis was used to elucidate the direction of the relationship between the variables. The outcome of this correlation indicated a significant negative relationship between mindfulness experience level and ERN difference score, suggesting that smaller ERN amplitudes are found in participants who have prior mindfulness experience, $r = -.380, p < .03$.

To examine the influence of worry on the ERN, a 2 x 2 x 4 mixed factorial ANOVA similar to that of the two previously described was performed with PSWQ score as a co-variate. No significant results were observed from this analysis, suggesting that scores on the PSWQ do not influence ERN amplitude.

Error Positivity (Pe)

The Pe was defined as the mean amplitude between 100 and 300 ms post-response. Pe data was analyzed using a 2 x 2 x 4 mixed factorial ANOVA with accuracy and site as within-subjects factors, and condition as a between-subjects factor. There was a significant main effect

of accuracy on Pe amplitude, such that Pe amplitude was larger, or more positive, following error trials ($M = 4.99 \mu\text{V}$, $SEM = .640$) than correct trials ($M = 1.23 \mu\text{V}$, $SEM = .253$), $F(1, 31) = 38.2$, $p < .001$. This result confirms the presence of the Pe during the Stroop test and supports the Pe as an error-related ERP peak. This analysis also revealed a significant main effect of site on Pe amplitude, $F(3, 93) = 5.80$, $p = .001$. Further, there was a significant interaction between accuracy and site, $F(3, 93) = 13.1$, $p < .001$. There was less difference between correct and error trials at the Pz site relative to the remaining three recording sites, and greater trial-based difference at frontal sites, indicating that the Pz was most prevalent at frontal sites on error trials. The mean peak amplitude of the Pe for correct and error trials at each of the four recording sites can be found in Table 1, and a group averaged Pe waveform for correct and error trials is depicted in Figure 1.

In order to test the influence of the mindfulness induction on the Pe, the effect of condition was analyzed. There was no significant main effect of condition on Pe amplitude, $F < 1$. Additionally, there was no significant interaction between accuracy and condition on Pe amplitude, indicating that condition did not effect Pe amplitude for correct or error trials $F < 1$. These two findings suggest that the mindfulness induction did not have an effect on the Pe.

A similar $2 \times 2 \times 4$ mixed factorial ANOVA was employed using STAI score as a covariate was employed to assess the effect of state anxiety on Pe amplitude. No effects of STAI score on any of the included variables reached statistical significance. However, there was a marginally significant main effect of STAI score on Pe amplitude, indicating a more positive Pe amplitude dependent on STAI score, regardless of trial type, $F(1, 30) = 3.66$, $p = .065$.

To ascertain the influence of worry on the Pe, a $2 \times 2 \times 4$ mixed factorial ANOVA with condition as a between-subjects factor, accuracy and site as within-subjects factors, and PSWQ

score as a co-variate was performed. Results showed a significant main effect of PSWQ score on Pe amplitude, $F(1, 30) = 8.16, p < .01$. Additionally, there was a significant interaction between accuracy and PSWQ score, $F(1, 30) = 8.57, p = .006$. Given these findings, a correlation analysis was used to determine the nature of the relationship between PSWQ score and Pe difference score (error minus correct amplitude). A significant negative correlation was revealed between PSWQ score and Pe difference score, showing that participants with higher levels of worry had a smaller Pe, $r = -.383, p < .03$.

To test the effect of previous mindfulness experience on the Pe, an identical ANOVA was performed, except with mindfulness experience level as a co-variate instead of PSWQ score. There were no significant results of this analysis, suggesting prior mindfulness exposure did not affect the Pe. A similar ANOVA analysis using awareness as a co-variate also produced no significant results, showing that awareness level did not impact Pe amplitude.

Error-Related Alpha Suppression (ERAS)

Error-related alpha suppression data was analyzed using a $2 \times 2 \times 5 \times 9$ mixed factorial ANOVA. The within-subjects factors included accuracy (error vs. correct), electrode site (Fz, F3, F4, Cz, C3, C4, Pz, P3, P4), and epoch within the 1280ms intertrial interval (divided into five epochs beginning at the time points 0, 256, 512, 768, and 1024 ms after button press response). Condition (mindfulness vs. control) was included as a between-subjects factor. There was a significant main effect of accuracy on ERAS in the predicted direction, such that alpha power was lower for error trials ($M = 1.42 \mu\text{V}, SEM = .052$) than for correct trials ($M = 1.47 \mu\text{V}, SEM = .051$), $F(1, 31) = 8.27, p = .007$.

Results of this ANOVA also revealed a significant main effect of epoch on alpha power, $F(4, 124) = 9.27, p < .001$. Specifically, in line with patterns of alpha activity characteristic of

ERAS, alpha power was lowest at the beginning epochs and peaked in the middle of the intertrial interval (Carp & Compton, 2009). For average alpha power means by epoch, refer to Table 2. Additionally, there was a significant interaction between epoch and accuracy, wherein alpha power increased over the ITI following correct trials, $F(4, 124) = 20.6, p < .001$. However, in line with previous work on ERAS, this rise in alpha was not present in the ITI following error commission (Carp & Compton, 2009). Alpha power separated by accuracy and epoch can be found in Table 2. Taken together, these results confirm the presence of alpha suppression following error trials on the Stroop task, and lend further support to the conceptualization of ERAS as an error-related neural phenomenon.

There was also a significant main effect of site on alpha power, wherein parietal recording sites showed more alpha activity than frontal sites, $F(8, 248) = 12.3, p < .001$. Average alpha power by recording site can be found in Table 3. A significant interaction between site and accuracy was also revealed, $F(8, 248) = 32.1, p < .001$. Average alpha power separated by site and accuracy is reported in Table 3. Results of this ANOVA also indicated a significant interaction between epoch and site, $F(32, 992) = 26.6, p < .001$. Additionally, there was a significant interaction between accuracy, epoch, and site, $F(32, 992) = 39.9, p < .001$. Given that the results pertaining to the relationships between accuracy and site, epoch and site, and accuracy, epoch, and site, are not relevant to the main hypotheses of the present study, they will not be explored further.

To inspect the effect of mindfulness on ERAS, the effect of condition was examined. There was no significant main effect of condition on alpha power, $F < 1$. However, there was a marginally significant interaction between accuracy and condition on alpha power, indicating that participants displayed different patterns of alpha power depending on condition for correct

and error trials, $F(1, 31) = 3.79, p = .06$. As a follow-up to this interaction effect, simple effects analyses were performed to examine the effect of accuracy on alpha for each condition separately. Results from the analysis of participants in the mindfulness condition indicated a significant simple main effect of accuracy on alpha power, $F(1, 14) = 7.79, p = .014$. Specifically, alpha power was significantly higher for correct trials than error trials, showing that the ERAS effect was present in the mindfulness condition. However, there was no significant simple main effect of trial accuracy for control participants, $F < 1$, indicating that alpha power was not affected trial accuracy for participants in this condition. Together, these results show that ERAS was present in participants in the mindfulness condition, but absent in control participants. Alpha power following correct and error trials for each condition can be found in Table 4, or in Figure 2 for a graphical representation.

Error-related alpha suppression was also examined with respect to several self-report measures, including STAI and PSWQ scores, and awareness and mindfulness experience levels. For each of these analyses, a $2 \times 2 \times 5 \times 9$ mixed factorial ANOVA was performed with the specific self-report measure as a co-variate. Based on the collective results of these four ANOVAs, none of the self-report variables had any influence on ERAS. These findings, as well as the effect of condition on alpha power reported above, indicate that ERAS was influenced by the mindfulness induction, yet it was not affected by individual differences. Importantly, ERAS was the only error-related neural component that responded to the mindfulness meditation manipulation.

Discussion

In an effort to expand upon current literature related to the mechanisms that underlie the benefits of mindfulness meditation, the present study was conducted to investigate the influence

of mindfulness on the neural process of error monitoring and behavioral performance. To assess the effect of mindfulness on these outcomes, the study employed a brief mindfulness induction and subsequently analyzed error-related neural markers and behavioral performance on a task of executive control. As indices of the brain's error monitoring system, physiological analysis focused on three neural correlates of error: the error-related negativity (ERN), the error positivity (Pe), and error-related alpha suppression (ERAS). The results indicate that the mindfulness induction successfully affected ERAS; however, there was no impact of this manipulation on ERN or Pe amplitudes, nor on performance on the Stroop task.

The present study was devised as a replication and extension of the research conducted by Larson, Steffen, and Primosch (2013) investigating the impact of a brief mindfulness meditation intervention on cognitive control and error-related performance monitoring. Aspects of the current study that replicated that of the Larson et al. study include implementation of an identical mindfulness intervention, collection of STAI scores, and assessment of the ERN, Pe, and behavioral performance on a task of cognitive control in response to the mindfulness intervention. On the other hand, the current study employed several study design changes in an effort to improve the validity of and expand upon the findings from Larson et al. (2013). First, instead of collecting depressive scores using the Beck Depression Inventory, the present study utilized the Penn State Worry Questionnaire to assess participants' existing levels of worry prior to engagement in the mindfulness induction. This design augmentation was utilized to prevent pre-existing worry levels from confounding the effect of mindfulness on ERP and behavioral outcomes. The current study also incorporated the Five Facet Mindfulness Questionnaire to balance conditions based on trait mindfulness, thereby reducing the opportunity for inherent mindfulness level to confound effects of the mindfulness manipulation. Finally, to expand upon

the study performed by Larson and his colleagues, the present study incorporated a third neural marker of error termed error-related alpha suppression, to assess whether the mindfulness induction may impact a broader scope of error-related phenomena.

The present study's first hypothesis addressed the relationship between mindfulness and a prevalent error-related phenomenon termed the ERN. The ERN's temporal placement early in the sequence of events that follow error commission suggests that this ERP component may reflect momentary awareness of an error. Given the increased awareness that characterizes mindfulness, it was hypothesized that participants exposed to a mindfulness induction would show an enhanced ERN following error trials, relative to control participants. Literature framing a heightened ERN as a component of an adaptive cognitive control system lends additional support to this hypothesis, as mindfulness has been used to increase adaptive responding and well-being in individuals suffering from psychological disorders (Ivanovski & Malhi, 2007). However, the results do not support this prediction. There was no effect of condition on ERN amplitude, suggesting that the mindfulness manipulation did not influence the ERN. This result fails to support findings of a study by Teper and Inzlicht (2013), wherein experienced meditators displayed a heightened ERN to error trials on a Stroop task, relative to controls with no previous meditation practice. Instead, the incapability of the mindfulness induction to influence the ERN coincides with findings of Larson and his colleagues (2013), whose study design was closely replicated by the present investigation.

In addition to the inability of the mindfulness manipulation to affect the ERN as expected, this error-related neural marker showed an unpredicted relationship with the two self-report measures of mindfulness collected in the present study. In particular, awareness, an important facet of mindfulness, was negatively correlated with ERN amplitude at a specific

recording site. The nature of the association between these two variables indicates that participants with low levels of awareness had heightened ERNs in response to error commission. The directionality of this correlation stands in opposition to existing research tying mindfulness to an enhanced ERN response, and counters the predicted association between these two variables. Prior mindfulness experience was also negatively correlated with the ERN, showing that participants with lower levels of mindfulness experience had larger ERN amplitudes. Similar to awareness, previous mindfulness experience demonstrated a relationship with the ERN in the reverse direction as predicted. Although a negative association between ERN amplitude and self-reported mindfulness was not expected, the relationships of awareness and prior mindfulness experience with the ERN follow in the same direction. Therefore, it appears that the ERN shares a negative relationship with mindfulness, contrary to much of the existing literature on mindfulness and the neural error monitoring process.

Continuing the trend of association between the ERN and individual difference measures, an unexpected, yet significant relationship emerged between the ERN and state anxiety level. Specifically, ERN amplitude was positively correlated with STAI score, revealing a link between the ERN and state anxiety. Although the present study conceptualized an enhanced ERN as an adaptive error response, this result appears to contradict this theory.

Although a positive relationship between the ERN and anxiety was not the focus of this study, there is substantial literature in support of this finding. The ERN has been reliably associated with individual differences in trait anxiety, and is often larger in people with anxiety and anxiety disorders, namely generalized anxiety disorder (Hajcak, 2012; Weinberg, Olvet, & Hajcak, 2010). In a study by Hajcak, McDonald, and Simons (2003), subjects with high general anxiety and worry showed enhanced error-related brain activity, as indexed by the ERN, relative

to a non-anxious control group. Given the ERN's well-documented relationship with anxiety, as well as the heritability and stability of this ERP component, some authors have argued that an enhanced ERN may serve as a biomarker of risk for anxiety disorders (Hajcak, 2012).

Furthermore, neurophysiological findings reveal an implication of the anterior cingulate cortex (ACC), a structure understood to be responsible for generation of the ERN, in regulation of affective and autonomic resources (Hajcak, McDonald, & Simons, 2004). This function of the ACC provides additional support to the connection between anxiety and the ERN, as anxiety is often accompanied by autonomic arousal. Although the existing literature generally reports a relationship between trait anxiety and a heightened ERN response, as opposed to state anxiety and the ERN, the observed correlation between anxiety and the ERN is grounded in previous research.

Together, the absence of an enhanced ERN response to the mindfulness induction and the observed relationship of the ERN with STAI scores and self-reported mindfulness brings into question the accuracy of the conceptualization of a heightened ERN as an adaptive error response. These results appear to be inconsistent with studies indicating that a larger ERN predicts improvements in academic performance, self-efficacy, emotional regulation, and stress management, as these imply an adaptive role of increased ERN (Hirsch & Inzlicht, 2009; Themanson et al., 2011; Teper & Inzlicht, 2013; Compton et al., 2013a). Specifically, enhancement of the ERN in response to a mindfulness induction would further support the notion of the ERN as an adaptive error response, given the wealth of data supporting mindfulness as a mechanism to increase adaptive responding and to promote mental well-being. However, the mindfulness manipulation did not influence the ERN, thereby weakening this line of reasoning. Additionally, the ERN was negatively correlated with two self-report measures of mindfulness,

suggesting that this error-related neural marker may actually represent a maladaptive error response. Moreover, the positive relationship between the ERN and anxiety lends additional support to the idea that the ERN is maladaptive. Collectively, none of the results of the present study support the notion of a larger ERN as a component of an adaptive cognitive control system.

Given the discrepancies that exist in the present study and previous literature regarding the adaptiveness of the ERN response, it is possible that the adaptive/maladaptive dichotomy as a conceptualization of the ERN is an oversimplification of the complex functions that this ERP component represents. The ERN has been reliably associated with both negative and positive phenomena, suggesting that this oppositional framework may not be appropriately suited for characterizing error-related neural phenomena, including the ERN.

The second hypothesis posited by this study concerned another error-related ERP component termed the error positivity (Pe). It was predicted that individuals exposed to a mindfulness induction would place less importance on their performance errors, resulting in decreased Pe amplitudes for participants in this condition relative to control participants. This proposal stems from the notion of the Pe as a reflection of error salience, and from literature framing mindfulness as a mechanism to relieve mental suffering. Following this line of reasoning, in a seminal study from which the present study was closely modeled, researchers reported attenuated Pe amplitudes in participants exposed to a brief mindfulness intervention (Larson et al., 2013). However, the present study failed to replicate this finding, as condition showed no influence on Pe amplitude. The inability of the current mindfulness manipulation to modify the Pe is especially surprising in light of results of the Larson et al. study, as well as other data relating meditation experience to depressed Pe amplitudes (Larson et al., 2013; Teper &

Inzlicht, 2013). Nonetheless, explorations of mindfulness and the Pe in the current study show a complete absence of relationship between these two variables, as the Pe was not related to individual differences in mindfulness or the mindfulness manipulation.

Although the Pe was not connected to mindfulness, it was negatively associated with scores on the PSWQ. Unexpectedly, participants with higher levels of worry showed smaller Pe amplitudes, suggesting that these participants may find their errors less salient. While this result was not predicted, it is supported by a line of research dedicated to error-related activity and individual differences in anxiety and worry. A similar relationship was reported in a study examining error-related psychophysiology and self-reported negative affect, wherein reduced Pe amplitude was associated with negative affect (Hajcak, McDonald, & Simons, 2004). Though negative affect is a distinct construct from worry as measured by the PSWQ, it is recognized as a trait tendency to experience negative feelings including anxiety and worry (Forgas, 2010). Given the tie between negative affectivity and worry, this result appears to support the association between PSWQ score and the Pe observed in the present study. Furthermore, depressive symptoms were associated attenuated Pe amplitudes in a study on the relationship between depression and error monitoring (Schroder, Moran, Infantolino, & Moser, 2013). Provided that worry is conceptually similar to rumination, a risk factor for depression, this finding upholds the directionality of the relationship between worry and the Pe illustrated by the present study (Fresco, Frankel, Mennin, Turk, & Heimberg, 2002).

The third hypothesis of the present study addressed the relationship between mindfulness and a recently recognized error-related neural marker, error-related alpha suppression (ERAS). Existing psychophysiological literature paints ERAS as an arousal response to errors, as well as a ruminative process given its temporal location in the sequence of error responding, and often

demonstrates an association between ERAS and negative phenomena (Compton et al., 2014; Compton et al., 2013a, 2013b; Compton, Goodman, Worby-Selim, unpublished). Therefore, it was proposed that mindfulness would reduce the presence of ERAS, as mindfulness is a tool for enhancing positive processes and reducing anxious arousal and ruminative processes. This hypothesis was not supported by the results, as ERAS was not attenuated in participants exposed to the mindfulness induction.

However, there was an effect of condition on alpha power, suggesting that the mindfulness induction influenced ERAS. Specifically, participants in the mindfulness condition showed higher alpha power relative to control participants. For participants in the mindfulness condition, there was also an effect of trial accuracy on alpha power, wherein alpha power was very high on correct trials relative to error trials, evidenced by a large reduction in alpha power from correct to error trials on the Stroop test. These patterns suggest that the mindfulness manipulation was successful in inducing a relaxed state during the study session, but that this state was not upheld when participants made an incorrect response. Interestingly, the control condition did not show typical alpha suppression, as there was no difference in alpha power between correct and error trials on the Stroop test in these participants. Together, these findings illustrate that the mindfulness group exhibited more error-related alpha suppression than the control group, and that this difference was driven by differential responding of alpha to correct trials, rather than error trials.

The increased alpha suppression in the mindfulness condition is unexpected, as it conflicts with much of the literature to date on ERAS. Since alpha power is inversely related to mental activation, suppression of alpha is thought to reflect an increase in mental activation and an arousal/alerting response to errors (Compton, Bissey, & Worby-Selim, 2014). Given the

notion of ERAS as an index of arousal, it is surprising that mindfulness, an aid in alleviating stress and worry, increased the presence of alpha suppression. This result is also unanticipated due to the wealth of research relating ERAS to negative phenomena, including greater cortisol reactivity, increased negative affect, less positive affect, more state anxiety, and additional blame-focused coping (Compton et al., 2013a, 2013b; Compton, Goodman, Worby-Selim, unpublished). These two pieces of evidence suggest that ERAS may represent a more maladaptive error response; however, the findings of the present study fail to support this notion.

One explanation of the increased ERAS in the mindfulness group is that this error-related activity may be an adaptive response, as the beneficial outcomes of mindfulness meditation suggest that this technique increases the presence of positive neurocognitive processes and activities. As reviewed above, substantial literature opposes the theory of ERAS as an adaptive response; however, there is also an adequate amount of research to defend this conceptualization of ERAS. In a series of studies devoted to the examination of ERAS and attention, results indicated that adaptation following attentional lapses, as indexed by posterror slowing on a sustained attention Simon task condition, involved alpha power suppression (van Driel et al., 2012). These results illustrate that task improvement was related to increased error-related suppression of alpha, and demonstrate a more adaptive role of ERAS.

An adaptive role of ERAS also lends well to the conflict-adaptation model of cognitive control. Researchers have suggested that experiencing conflict on a task trial can lead to adjustment or adaptation processes, as evidenced by performance on the subsequent trial (Botvinick, Braver, Barch, & Cohen, 2001). The negative relationship between alpha and mental activation suggests that reduction of alpha reflects an increase in cerebral activity. A study by Compton, Arnstein, Freedman, Dainer-Best, and Liss (2011) postulated that this reduction in

alpha following conflict (error) trials supports the idea that the presence of conflict leads to an active process of cognitive control. Thus, it is possible that error-related alpha suppression increases cerebral activity related to the process of adjusting attentional filters and implementing cognitive control. These studies, as well as the findings observed in the present investigation, suggest that ERAS represents an adaptive error response. Provided the increase in alpha suppression to the mindfulness manipulation in the current study, the adaptive conceptualization of ERAS fits nicely with the literature on mindfulness and adaptive responding related to mental health gains. However, as previously mentioned, discrepancies in the literature related to the adaptive nature of ERAS suggest that the classification of error-related neural correlates into adaptive versus maladaptive responses may not be the most useful framework for understanding these phenomena.

The final hypotheses proposed by this study concerned behavioral performance on the Stroop test. Although behavioral outcomes of mindfulness were not central to the present study, both accuracy and efficiency data were collected to assess the influence of the mindfulness induction on performance. In previous research, novice meditators showed improved performance and greater efficiency on the Stroop task compared to a control condition after engaging in meditation exercises (Wenk-Sormaz, 2005). Based on these findings, it was hypothesized that participants in the mindfulness condition would display improved performance on the Stroop test, as indexed by increased accuracy and efficiency. Contrary to these hypotheses, accuracy and reaction time were not affected by condition, demonstrating no added benefit of the mindfulness manipulation on performance. These results cannot be attributed to participants' lack of understanding of the task, as participants included in these analyses displayed typical Stroop performance.

A possible explanation for the lack of differences between conditions in behavioral performance is the implementation of a brief induction to generate a state of mindfulness, and the naivety of participants to mindfulness meditation. The only other study to report enhanced performance in response to mindfulness meditation using electrophysiological methods included a sample of experienced meditators who had already developed aptitude in awareness and acceptance (Teper & Inzlicht, 2013). Therefore, it is possible that the skills acquired by frequent participation in meditation may be necessary to attain behavioral improvement, and that these gains cannot be achieved by a brief intervention staged on participants with little to no prior mindfulness experience. This explanation is supported by findings of Larson, Steffen, and Primosch (2013) who found no effect on performance outcomes of a mindfulness induction identical to the one utilized in the present study.

Taken together, the results of this study demonstrate that error-related neural phenomena are predicted in complex ways by mindfulness and anxiety, instead of converging into a cohesive conclusion regarding mindfulness and error-related neural activity. Though ERAS was responsive to the mindfulness induction, the ERN and Pe displayed no reaction to this manipulation. Instead, these error-related ERP components were related to individual differences in mindfulness and anxiety. The ERN's specific relationship with state anxiety, mindfulness experience, and awareness, as well as the lack of effect of the mindfulness manipulation on the ERN, introduce the possibility that this ERP component reflects a less adaptive error response than previously hypothesized.

A second ERP component, the Pe, was also not affected by the mindfulness manipulation. However, attenuated Pe amplitudes were related to higher levels of pathological worry. Provided the notion of the Pe as an reflection of error salience, it is possible that

individuals are too preoccupied with the repetitive verbal activity to generate possible negative outcomes that characterizes worry to lend neurocognitive resources to performance monitoring (Roemer & Orsillo, 2002). Thus, the importance placed on performance errors is reduced in individuals who are engaged in worry.

On the other hand, the mindfulness induction did influence the presence of ERAS, such that individuals exposed to the manipulation showed increased suppression of alpha relative to control participants. While ERAS was conceived as a maladaptive error process, this result more closely corresponds with literature supporting a more adaptive function of ERAS, as it is expected that mindfulness encourages the presence of adaptive processes. However, the mindfulness induction had no influence on behavioral performance, thus it remains unclear whether this manipulation actually gave rise to better-adjusted practices. Importantly, the present study is the first to examine the relationship between mindfulness and ERAS and to show an effect of a mindfulness induction on suppression of alpha.

Strengths

A major strength of the present study was its ability to demonstrate typical and predicted ERN and Pe peaks, a typical pattern of error-related alpha suppression, and expected Stroop interference effects during a behavioral task of cognitive control. Because the error-related ERP and oscillatory components analyzed in the study were significant, and Stroop performance showed standard congruency effects, the foundation for assessing the influence of mindfulness on these variables was sturdy. Although none of the proposed hypotheses were supported, the prerequisites for testing these hypotheses were met. Relatedly, though the main hypothesis regarding the ERAS was not supported, the present study is the first to show an effect of

mindfulness on ERAS. Although the effect of the mindfulness induction on ERAS was not in the expected direction, this result remains strong and unique to the current investigation.

One strong aspect of the current study's design was the mindfulness induction. The particular mindfulness manipulation used by the present study was modeled after a brief mindfulness intervention shown to be effective in a study assessing the effects of mindfulness on cognitive control and error-related performance monitoring (Larson et al., 2013). Though this mindfulness manipulation did not prove as effective in the current study as we had hoped, it did affect ERAS. The influence of this manipulation on ERAS suggests that the mindfulness induction was at least somewhat successful in generating physiological changes in the brain.

A second important strength of the study design was the balance of condition based on trait mindfulness levels. This particular feature of the present study's design was implemented to improve upon the Larson et al. study after which it was modeled. The inclusion of this measure allowed for more accurate analysis of the influence of the mindfulness induction on electrophysiological and behavioral data through elimination of trait mindfulness as a potential confound. Therefore, any results related to the effect of the mindfulness induction cannot be attributed to the pre-existing mindfulness of participants. Additionally, gender did not differ with respect to condition, nor did it relate to any of the psychophysiological or self-report outcomes, thereby negating any potential for this demographic factor to have masked or fashioned effects related to condition.

Limitations

A challenge to many studies that examine the influence of a particular state on psychophysiological or behavioral outcomes is whether their manipulation successfully brought about a change in this particular state. In the present study, we hoped to manipulate the mental

state of our participants and generate a mindset of mindfulness through a mindfulness induction. However, there are some aspects of the study's design and results that suggest that the mindfulness manipulation may not have been as successful as anticipated. First, the mindfulness manipulation involved a brief, fourteen-minute, mindfulness of breathing exercise. While this particular form of induction was chosen given its success in creating psychophysiological changes in a prior study of mindfulness and error monitoring, it is possible that this induction was too transient in nature to produce a lasting mindful state (Larson et al., 2013). This proposal is supported by the inability of the manipulation to influence the ERN, the Pe, and behavioral performance. On the other hand, the significant effect of condition on ERAS suggests that the mindfulness induction was successful in producing psychophysiological changes. However, it is unclear whether the manipulation simply made participants more relaxed, or whether they were truly more mindful. Given these lines of reasoning, it may be hard to manipulate mindfulness in a laboratory setting. It is important to note that the difficulty of manipulating mindfulness and related mental states is not unique to the present investigation. Rather, this is a common limitation shared across studies that attempt to enact similar state manipulations, such as anxiety and emotion regulation.

A potential limitation to the present study was the confounding variable of worry, as analysis revealed that scores on the PSWQ were significantly higher for control participants than for participants in the mindfulness condition. Although experimenters specifically balanced trait mindfulness across condition, this precautionary measure was not taken with respect to worry level. This limitation makes it difficult to ascertain whether the effects of condition were truly caused by the mindfulness manipulation, or whether these results were a product of pre-existing levels of worry. However, it is unlikely that the outcomes observed in the study are attributable

to participants' level of worry, as scores on the PSWQ were significantly associated with only one dependent psychophysiological measure. While scores on the PSWQ were significantly correlated with the Pe, they were not related to the remaining two error-related phenomena or behavioral performance. Therefore, this confound may not have had a strong influence on results concerning condition.

Future Directions

Provided the limitations reviewed above, future studies should implement a few design changes in order to improve the success and validity of future manipulations. Importantly, studies examining the effect of mindfulness on psychophysiological and behavioral outcomes should utilize more in-depth mindfulness manipulations. Much of the research to date that has reported significant influences of mindfulness on anxious responding, depressive symptoms, and other mental health effects employed interventions spanning several weeks. In addition to the broad time-course of these studies, most successful mindfulness interventions are accompanied by take-home exercises that are performed outside of the mindfulness laboratory sessions. These interventions, compared to the brief induction utilized by the present study, are undoubtedly more in-depth and extensive. Given the available time frame in which to conduct the present study, this option was not viable. Thus, future research may want to consider an intervention that spans a longer time-course to manipulate mindfulness and to assess psychophysiological responses to the manipulation.

In a related vein, it would be interesting to investigate the efficacy of mindfulness manipulations of differing time-courses and intensities on psychophysiological and behavioral outcomes. Although it is unlikely that a brief induction could produce the mental health benefits attained from weeklong mindfulness programs, it is unclear whether such an extensive

mindfulness rubric is necessary to observe psychophysiological changes. While the present study's findings seem to support the argument that a more in-depth mindfulness manipulation is necessary to create psychophysiological changes, another study found the same, brief mindfulness induction to be successful in bringing about significant modifications in specific ERP components (Larson et al., 2013). To address this disparity, additional studies may consider comparing the psychophysiological and behavioral effects of a brief mindfulness induction to those of a long, in-depth mindfulness intervention.

Another possible direction for future study is to examine the effect of longer-term mindfulness interventions on ERAS, as the current study showed that this error-related neural phenomenon responded to a brief mindfulness induction. It is conceivable that the relationship between mindfulness and ERAS may become stronger and better defined in a study that employs a stronger manipulation. Further evaluation of ERAS also warrants additional research to determine whether the effect of mindfulness on ERAS observed in the present study can be replicated.

A final suggestion for future research stems from a limitation observed in the present study. Provided that the mindfulness and control conditions differed with respect to worry level, future work may consider balancing groups based on levels of worry and anxiety in order to reduce the ability of these variables to confound or mask significant results. Although this was a limitation of the current study that did not appear to drastically confound major results, it is important to control for anxiety and worry specifically, as these are mental states that are often influenced by mindfulness in its effects on mental health.

In summary, our results suggest that a mindfulness induction administered in a single session had an impact on ERAS, but did not immediately influence ERN or Pe amplitudes, or

behavioral performance. Future research employing more in-depth mindfulness manipulations and that control for trait characteristics such as worry and anxiety would provide a necessary advance in understanding the role of mindfulness in the psychophysiological and behavioral mechanisms that underlie the benefits of mindfulness meditation.

References

- Baer, R. A., Smith, G. T., Lykins, E., Button, D., Krietemeyer, J., Sauer, S., et al. (2008). Construct validity of the five facet mindfulness questionnaire in meditating and nonmeditating samples. *Assessment, 15*(3), 329-342.
- Başar, E., Başar-Eroglu, C., Karakaş, S., & Schürmann, M. (2001). Gamma, alpha, delta, and theta oscillations govern cognitive processes. *International Journal of Psychophysiology, 39*(2), 241-248.
- Bishop, S. R., Lau, M., Shapiro, S., Carlson, L., Anderson, N. D., Carmody, J., Segal, Z. V., Abbey, S., Speca, M., Velting, D., & Devins, G. (2004). Mindfulness: A proposed operational definition. *Clinical Psychology: Science and Practice, 11*(3), 230-241.
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 624–652.
- Brown, K. W., & Ryan, R. M. (2003). The benefits of being present: mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology, 84*(4), 822-848.
- Brown, K. W., Goodman, R. J., & Inzlicht, M. (2012). Dispositional mindfulness and the attenuation of neural responses to emotional stimuli. *Social Cognitive and Affective Neuroscience, 1-7*.
- Cahn, B. R., & Polich, J. (2013). Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychology of Consciousness: Theory, Research, and Practice, 1*, 48-96.
- Carp, J., & Compton, R. J. (2009). Alpha power is influenced by performance errors. *Psychophysiology, 46*(2), 336-343.
- Chambers, R., Lo, B. C. Y., & Allen, N. B. (2007). The impact of intensive mindfulness training

- on attentional control, cognitive style, and affect. *Cognitive Therapy and Research*, 32(3), 303-322.
- Chan, D., & Woollacott, M. (2007). Effects of level of meditation experience on attentional focus: is the efficiency of executive or orientation networks improved?. *The Journal of Alternative and Complementary Medicine*, 13(6), 651-658.
- Chiesa, A., & Serretti, A. (2010). A systematic review of neurobiological and clinical features of mindfulness meditations. *Psychological medicine*, 40(08), 1239-1252.
- Chiesa, A., Calati, R., & Serretti, A. (2011). Does mindfulness training improve cognitive abilities? A systematic review of neuropsychological findings. *Clinical psychology review*, 31(3), 449-464.
- Clark, L.A., Watson, D., Mineka S. (1994). Temperament, personality, and the mood and anxiety disorders. *Journal of Abnormal Psychology*, 103(1), 103–116.
- Coffey, K. A., Hartman, M., & Fredrickson, B. L. (2010). Deconstructing mindfulness and constructing mental health: understanding mindfulness and its mechanisms of action. *Mindfulness*, 1(4), 235-253.
- Compton, R. J., Robinson, M. D., Ode, S., Quandt, L. C., Fineman, S. L., & Carp, J. (2008). Error-monitoring ability predicts daily stress regulation. *Psychological Science*, 19(7), 702-708.
- Compton, R. J., Arnstein, D., Freedman, G., Dainer-Best, J., & Liss, A. (2011). Cognitive control in the intertrial interval: evidence from EEG alpha power. *Psychophysiology*, 48(5), 583-590.
- Compton, R. J., Arnstein, D., Freedman, G., Dainer-Best, J., Liss, A., & Robinson, M. D. (2011).

- Neural and behavioral measures of error-related cognitive control predict daily coping with stress. *Emotion*, *11*(2), 379-390.
- Compton, R. J., Hofheimer, J., & Kazinka, R. (2013a). Stress regulation and cognitive control: evidence relating cortisol reactivity and neural responses to errors. *Cognitive, Affective, & Behavioral Neuroscience*, *13*(1), 152-163.
- Compton, R. J., Hofheimer, J., Kazinka, R., Levinson, A., & Zheutlin, A. (2013b). Alpha suppression following performance errors is correlated with depression, affect, and coping behaviors. *Emotion*, *13*(5), 905-914.
- Compton, R. J., Bissey, B., & Worby-Selim, S. (2014). Task motivation influences alpha suppression following errors. *Psychophysiology*, *51*, 585-595.
- Forgas, J. (2010). Cognitive Theories of Affect. *Corsini Encyclopedia of Psychology*: 1–3.
- Fresco, D. M., Frankel, A. N., Mennin, D. S., Turk, C. L., & Heimberg, R. G. (2002). Distinct and overlapping features of rumination and worry: The relationship of cognitive production to negative affective states. *Cognitive Therapy and Research*, *26*(2), 179-188.
- Gross, J. (2002) Emotion regulation: Affective, cognitive, and social consequences. *Psychophysiology*, *39*, 281–291.
- Hajcak, G., McDonald, N., & Simons, R. F. (2004). Error-related psychophysiology and negative affect. *Brain and Cognition*, *56*(2), 189-197.
- Hajcak, G. (2012). What we've learned from mistakes: Insights from error-related brain activity. *Current Directions in Psychological Science*, *21*(2), 101-106.
- Hirsch, J. B., & Inzlicht, M. (2010). Error-related negativity predicts academic performance. *Psychophysiology*, *47*(1), 192-196.

- Hofmann, S. G., Sawyer, A. T., Witt, A. A., & Oh, D. (2010). The effect of mindfulness-based therapy on anxiety and depression: A meta-analytic review. *Journal of Consulting and Clinical Psychology, 78*(2), 169.
- Ito, T. A., Larsen, J. T., Smith, N. K., & Cacioppo, J. T. (1998). Negative information weighs more heavily on the brain: the negativity bias in evaluative categorizations. *Journal of Personality and Social Psychology, 75*(4), 887-900.
- Ivanovski, B., & Malhi, G. S. (2007). The psychological and neurophysiological concomitants of mindfulness forms of meditation. *Acta Neuropsychiatrica, 19*(2), 76-91.
- Jha, A. P., Krompinger, J., & Baime, M. J. (2007). Mindfulness training modifies subsystems of attention. *Cognitive, Affective, & Behavioral Neuroscience, 7*(2), 109-119.
- Kabat-Zinn, J. (1982). An outpatient program in behavioral medicine for chronic pain patients based on the practice of mindfulness meditation: Theoretical considerations and preliminary results. *General Hospital Psychiatry, 4*(1), 33-47.
- Kabat-Zinn, J. (1990). *Full catastrophe living: Using the wisdom of your body and mind to face stress, pain, and illness*. New York: Delacorte.
- Kabat-Zinn, J., Massion, A. O., Kristeller, J., Peterson, L. G., Fletcher, K., Pbert, L., et al. (1992). Effectiveness of a meditation-based stress reduction program in the treatment of anxiety disorders. *American Journal of Psychiatry, 149*, 936-943.
- Kabat-Zinn, J. (2003). Mindfulness-based interventions in context: Past, present, and future. *American Psychological Association*.
- Kappenman, E. S., & Luck, S. J. (2012). ERP components: The ups and downs of brainwave recordings. *Oxford Handbook of ERP Components*.
- Kumar, S., Feldman, G., & Hayes, A. (2008). Changes in mindfulness and emotion regulation in

- an exposure-based cognitive therapy for depression. *Cognitive Therapy and Research*, 32(6), 734-744.
- Kuyken, W., Byford, S., Taylor, R. S., Watkins, E., Holden, E., White, K., Barrett, B., Byng, R., Evans, A., Mullan, E., & Teasdale, J. D. (2008). Mindfulness-based cognitive therapy to prevent relapse in recurrent depression. *Journal of Consulting and Clinical Psychology*, 76(6), 966-978.
- Larson, M. J., Steffen, P. R., & Primosch, M. (2013). The impact of a brief mindfulness meditation intervention on cognitive control and error-related performance monitoring. *Frontiers in Human Neuroscience*, 7, 1-12.
- Luck, S. J. (2005). An introduction to the event-related potential technique. Cambridge, MA: Massachusetts Institute of Technology Press.
- Lutz, A., Slagter, H. A., Dunne, J. D., & Davidson, R. J. (2008). Attention regulation and monitoring in meditation. *Trends in Cognitive Sciences*, 12(4), 163-169.
- Ma, S. H., & Teasdale, J. D. (2004). Mindfulness-based cognitive therapy for depression: replication and exploration of differential relapse prevention effects. *Journal of Consulting and Clinical Psychology*, 72(1), 31-40.
- Malinowski, P. (2013). Neural mechanisms of attentional control in mindfulness meditation. *Frontiers in neuroscience*, 7(8), 1-11.
- Meyer, T. J., Miller, M. L., Metzger, R. L., & Borkovec, T. D. (1990). Development and validation of the penn state worry questionnaire. *Behaviour Research and Therapy*, 28(6), 487-495.
- Miller, J. J., Fletcher, K., & Kabat-Zinn, J. (1995). Three-year follow-up and clinical

- implications of a mindfulness meditation-based stress reduction intervention in the treatment of anxiety disorders. *General Hospital Psychiatry*, 17(3), 192-200.
- Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and Cognition*, 18(1), 176-186.
- Moore, A., Gruber, T., Deroose, J., & Malinowski, P. (2012). Regular, brief mindfulness meditation practice improves electrophysiological markers of attentional control. *Frontiers in human neuroscience*, 6, 1-15.
- Moser, J. S., Moran, T. P., Schroder, H. S., Donnellan, M. B., & Yeung, N. (2013). On the relationship between anxiety and error monitoring: a meta-analysis and conceptual framework. *Frontiers in Human Neuroscience*, 7, 1-19.
- Mrazek, M. D., Smallwood, J., & Schooler, J. W. (2012). Mindfulness and mind-wandering: finding convergence through opposing constructs. *Emotion*, 12(3), 442-448.
- Overbeek, T. J., Nieuwenhuis, S., & Ridderinkhof, K. R. (2005). Dissociable components of error processing: On the functional significance of the Pe vis-à-vis the ERN/Ne. *Journal of Psychophysiology*, 19(4), 319-329.
- Pargament, K. I. (2013). APA Handbook of Psychology, Religion, and Spirituality: Context, Theory, and Research. *American Psychological Association*, 1, 311-327.
- Perlman, D. M., Salomons, T. V., Davidson, R. J., & Lutz, A. (2010). Differential effects on pain intensity and unpleasantness of two meditation practices. *Emotion*, 10, 65-71.
- Posner, M. I., and Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, 13, 25-42.
- Ramel, W., Goldin, P. R., Carmona, P. E., & McQuaid, J. R. (2004). The effects of mindfulness

- meditation on cognitive processes and affect in patients with past depression. *Cognitive Therapy and Research*, 28(4), 433-455.
- Ridderinkhof, K. R., Ramautar, J. R., & Wijnen, J. G. (2009). To PE or not to PE: A P3-like ERP component reflecting the processing of response errors. *Psychophysiology*, 46(3), 531-538.
- Roemer, L., & Orsillo, S. M. (2002). Expanding our conceptualization of and treatment for generalized anxiety disorder: Integrating mindfulness/acceptance-based approaches with existing cognitive-behavioral models. *Clinical Psychology: Science and Practice*, 9(1), 54-68.
- Schroder, H. S., Moran, T. P., Infantolino, Z. P., & Moser, J. S. (2013). The relationship between depressive symptoms and error monitoring during response switching. *Cognitive, Affective, & Behavioral Neuroscience*, 13(4), 790-802.
- Spielberger, C. D. (2010). State-Trait Anxiety Inventory. In *Corsini Encyclopedia of Psychology*, 1. Retrieved from:
<http://onlinelibrary.wiley.com/doi/10.1002/9780470479216.corpsy0943/full>
- Teasdale, J. D., Segal, Z. V., Williams, J. M. G., Ridgeway, V. A., Soulsby, J. M., & Lau, M. A. (2000). Prevention of relapse/recurrence in major depression by mindfulness-based cognitive therapy. *Journal of Consulting and Clinical Psychology*, 68(4), 615.
- Tang, Y. Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., et al. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings of the National Academy of Sciences*, 104(43), 17152-17156.
- Teper, R., & Inzlicht, M. (2013). Meditation, mindfulness and executive control: the importance

- of emotional acceptance and brain-based performance monitoring. *Social cognitive and affective neuroscience*, 8(1), 85-92.
- Teper, R., & Inzlicht, M. (2014). Mindful acceptance dampens neuroaffective reactions to external and rewarding performance feedback. *Emotion*, 14(1), 105-114.
- Themanson, J. R., Pontifex, M. B., Hillman, C. H., & McAuley, E. (2011). The relation of self-efficacy and error-related self-regulation. *International Journal of Psychophysiology*, 80(1), 1-10.
- Valentine, E. R., & Sweet, P. L. (1999). Meditation and attention: A comparison of the effects of concentrative and mindfulness meditation on sustained attention. *Mental Health, Religion & Culture*, 2(1), 59-70.
- van den Hurk, P. A., Giommi, F., Gielen, S. C., Speckens, A. E., & Barendregt, H. P. (2010). Greater efficiency in attentional processing related to mindfulness meditation. *The Quarterly Journal of Experimental Psychology*, 63(6), 1168-1180.
- van Driel, J., Ridderinkhof, K. R., & Cohen, M. X. (2012). Not all errors are alike: theta and alpha EEG dynamics relate to differences in error-processing dynamics. *The Journal of Neuroscience*, 32(47), 16795-16806.
- Weinberg, A., Olvet, D. M., & Hajcak, G. (2010). Increased error-related brain activity in generalized anxiety disorder. *Biological Psychology*, 85(3), 472-480.
- Wenk-Sormaz, H. (2005). Meditation can reduce habitual responding. *Advances in Mind-Body Medicine*, 21, 33-49.

Tables and Figures

Table 1. *Average Peak Amplitude of Error Positivity (Pe) for Correct and Error Trials at Electrode Site*

Electrode Site	Correct Trials (μV)	Error Trials (μV)
Fz	.845	4.91
FCz	.842	5.64
Cz	.840	4.53
Pz	2.37	4.89

Table 2. *Average Alpha Power By Epoch and for Correct and Error Trials*

Epoch (ms)	Correct Trials (μV)	Error Trials (μV)	Average (μV)
0	1.36	1.46	1.41
256	1.46	1.35	1.40
572	1.50	1.39	1.45
768	1.52	1.44	1.48
1024	1.49	1.45	1.47

Table 3. *Average Alpha Power by Site and for Correct and Error Trials*

Site	Correct Trials (μV)	Error Trials (μV)	Average (μV)
F3	1.53	1.36	1.44
Fz	1.56	1.35	1.45
F4	1.50	1.40	1.45
C3	1.45	1.42	1.44
Cz	1.37	1.49	1.43
C4	1.40	1.44	1.42
P3	1.40	1.46	1.43
Pz	1.45	1.44	1.44
P4	1.52	1.40	1.46

Table 4. *Average Alpha Power Across Condition for Correct and Error Trials*

Condition	Correct Trials (μV)	Error Trials (μV)
Mindfulness	1.53	1.45
Control	1.40	1.39

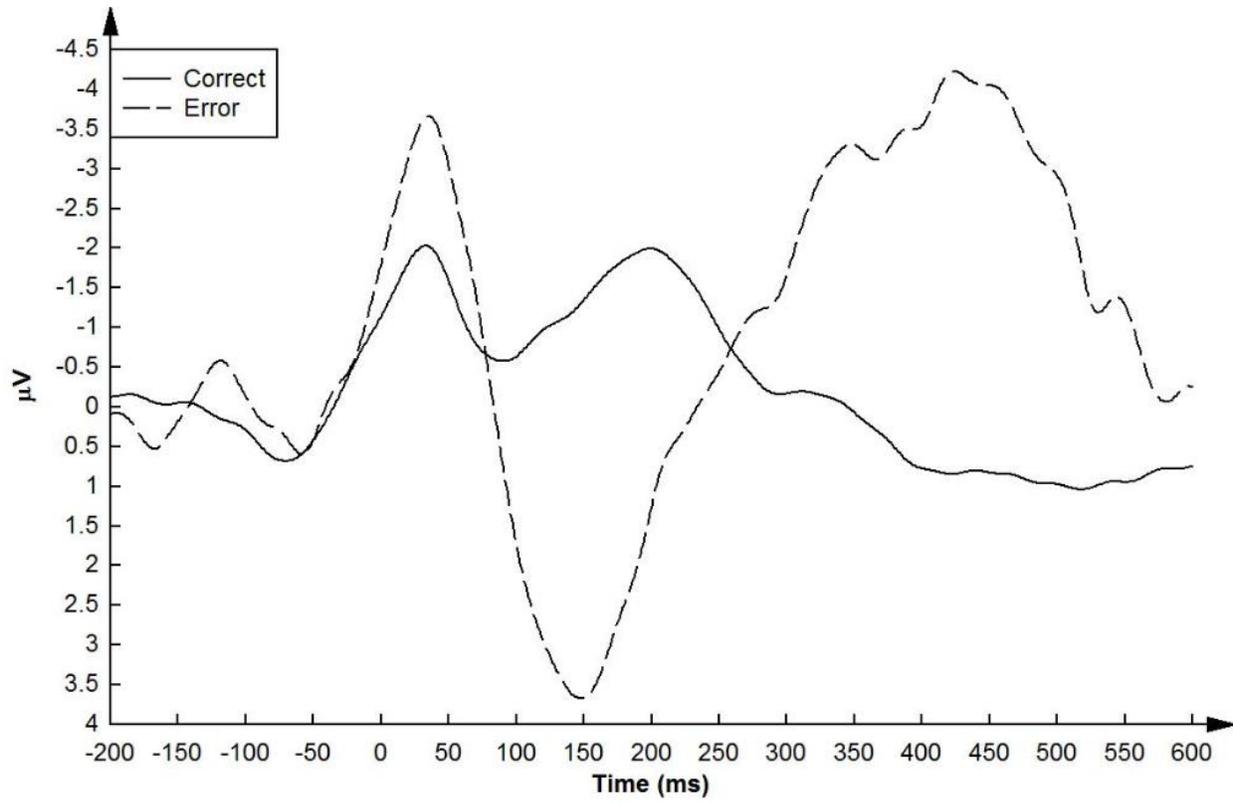


Figure 1. Average event-locked potentials for correct and error trials at the FCz site. Time 0 is the time of button press.

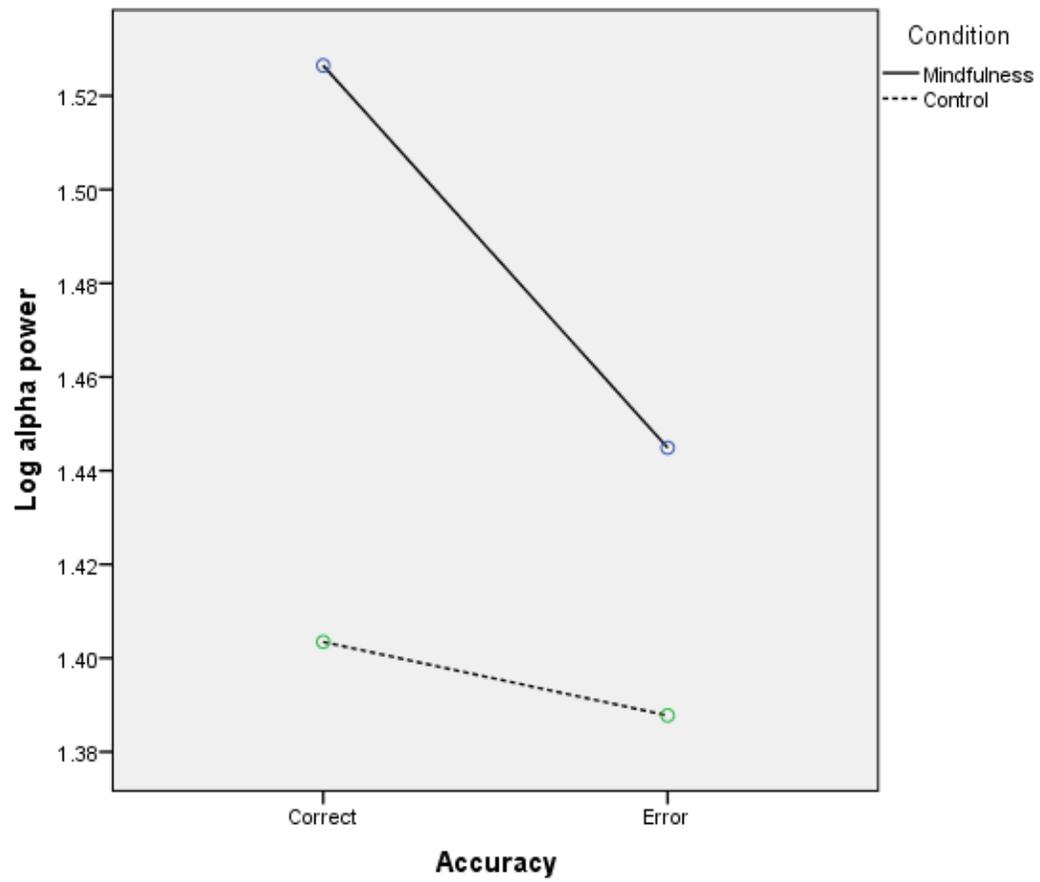


Figure 2. Log alpha power values for correct and error trials by condition.