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The Effects of a Mindfulness Induction on the Brain's Response to Performance Errors

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Abstract

The current study aimed to investigate the effects of a mindfulness induction on the brain's response to performance errors, specifically whether a mindfulness induction would affect cognitive performance and the neural correlates of performance monitoring. Three neural correlates of performance monitoring were examined: the error-related negativity (ERN), error positivity (Pe), and error-related alpha suppression (ERAS). The mindfulness induction was intended to induce mindful awareness via a short audio clip with meditative breathing exercises, whereas the control condition simply listened to an educational audio clip on mindfulness. All participants then completed a Stroop test while EEG was recorded. The groups showed similar performance on the Stroop test, and ERN and Pe amplitudes did not differ across groups. However, alpha power was marginally different across groups, where those in the mindfulness condition showed higher alpha power following correct trials than error trials. Moreover, several different measures of individual differences, including awareness level, anxiety level, worry level, and mindfulness experience level were associated with these neural correlates. The results may reflect the idea that neural responses to errors are affected differently by a mindfulness induction and are predicted by various measures of individual differences in complex ways.

## Introduction

Mindfulness meditation is often viewed as a form of mental training and has received considerable attention in neuroscience research over the past few decades. The powerful and beneficial effects of mindfulness meditation and its associated mental and physical health-related benefits have sparked a surge in interest recently, particularly as individuals search for alternatives to medicine to manage various life stressors. Both short-term mindfulness inductions and long-term mindfulness interventions have been found to alleviate stress, pain, and various psychological illnesses such as depression and anxiety, as well as enhance other psychological capacities such as attention, emotion regulation, and executive control. Nonetheless, despite the growing interest in mindfulness and its clinical applications in improving mental and physical health, it is still a relatively new research field of interest whose underlying mechanisms remain unclear.

Mindfulness is commonly known as the state of being aware of and attentive to the present moment, and entails the development and cultivation of particular qualities of attention and awareness through meditation and conscious attention (Kabat-Zinn, 2003). It primarily comprises two features: awareness, or acknowledging one's thoughts and feelings, and acceptance, or acquiescently approving of one's thoughts and feelings. Kabat-Zinn (2003) provided an operational definition of mindfulness, stating that it is "the awareness that emerges through paying attention on purpose, in the present moment, and nonjudgmentally to the unfolding of experience moment by moment" (Kabat-Zinn, 2003, p. 145). Mindfulness is essentially non-judgmental attention to present moment experiences and therefore requires both the regulation of attention and the ability to approach experiences and sensations with openness and acceptance.

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There are many different styles and forms of mindfulness practice found in numerous cultures and religions. Mindfulness meditation originates in Buddhist traditions and meditation practice. Buddhist meditation practice promotes the cultivation of mind and heart through awareness and mindful attention of the present moment in order to reduce suffering and enhance personal development (Goldstein, 2002). Mindfulness practice is not merely a rehearsal of the various techniques that allow one to engage in mindful attention; rather, it involves the cultivation of awareness and emotional acceptance of the present moment in order to know the direct experience in each moment (Kabat-Zinn, 2003). It entails being open to all aspects of experience that occur both in the mind and the body, the purpose of which is to remain in the present moment, and free of concern about the past or the future. These Buddhist traditions of mindfulness practice have become well-established in the West in recent decades and have been found to be effective ways to improve mental and physical health.

The first formal incorporation of mindfulness into the medical field occurred in 1979 at an outpatient Stress Reduction Clinic offered at the University of Massachusetts Medical Center. Mindfulness-based stress reduction (MBSR) was developed at the outpatient clinic to specifically relieve suffering and reduce stress in medical patients through intense mindfulness meditation and its applications to both the mental and physical effects of stress, pain, and illness (Kabat-Zinn, 2003). The MBSR clinic consisted of an eight-week course featuring both education on mindfulness as well as applied mindfulness practice, with the aim of encouraging patients to participate more fully in their process toward greater mental and/or physical health. As more attention has been given to the beneficial effects of mindfulness on psychological health, researchers have shown that mindfulness-based interventions can reduce many forms of psychological distress, including generalized anxiety disorder (Kabat-Zinn et al., 1992),

depression (Shapiro, Schwartz, & Bonner, 1998; Speca, Carlson, Goodey, & Angen, 2000), and depressive relapse (Teasdale, Segal, Williams, Ridgeway, Soulsby, & Lau, 2000).

In addition to improving mental and physical health, mindfulness has been shown to improve various aspects of executive control, particularly attention (Chambers, Lo, & Allen, 2007; Jha, Krompinger, & Baime, 2007; Moore & Malinowski, 2009; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010). Executive control allows individuals to overcome impulses and override involuntary behavior, abilities that are essential for emotion regulation and peak performance (Compton, Robinson, Ode, Quandt, Fineman, & Carp, 2008). An important aspect of executive control is performance monitoring, a cognitive process that compares current behavior to idealized behavior or a desired outcome. Researchers have linked performance monitoring to mindfulness, suggesting that meditation practice is a form of performance monitoring itself, as it requires people to monitor their minds and redirect attention to the present moment (Teper & Inzlicht, 2013). While there is a considerable amount of evidence supporting the beneficial effects of mindfulness meditation on executive function, research is now seeking to understand the underlying neurophysiological mechanisms behind this effect. Understanding the underlying brain processes could be useful in improving mindfulness-based inductions and interventions, which have been initially successful in improving the mental and physical health of patients with various clinical disorders.

The purpose of the present study is to examine the effects of a brief mindfulness induction on the neural correlates of performance monitoring in order to gain insight into the neural mechanisms underlying the beneficial effects of mindfulness. We aim to discover how the brain's response to errors is altered following a mindfulness induction, which could have important clinical applications. Since many who suffer from psychological disorders struggle

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with rumination and often exhibit maladaptive responses to mistakes and negative life stressors, a better understanding of the neural mechanisms involved in the interaction of mindfulness and error-processing may foster the development of new and refined mindfulness training techniques that can benefit these individuals.

### *Mindfulness and Well-being*

Mindfulness and meditation practice has been shown to be very beneficial to both psychological and physical well-being. For example, dispositional and state mindfulness has been found to predict positive emotional states and enhanced self-regulation (Brown & Ryan, 2003). As the interest in mindfulness has increased over the past few decades, researchers have begun to incorporate mindfulness practice into various forms of therapy. In particular, mindfulness-based group interventions, such as mindfulness-based stress reduction (MBSR; Kabat-Zinn, 1990) and mindfulness-based cognitive therapy (MBCT; Segal, Williams, & Teasdale, 2002), have aided many patients in effectively managing both physical and mental health symptoms, such that patients who engaged in these programs often showed improved symptoms and mechanisms of coping.

The first formal mindfulness intervention, MBSR, is a structured eight-ten week clinical group program that employs mindfulness meditation to alleviate suffering associated with many physical and psychological disorders. It entails systematic training in mindfulness meditation as a self-regulatory approach to reduce stress and manage emotions. Each session focuses on topics and exercises within the framework of mindfulness, with particular emphasis on mindful concentration regarding one's physical sensations, such as sensations from specific body parts or feelings of breathing (Kabat-Zinn, 1990). The goal of the MBSR meditation techniques is to improve one's ability to remain in the present moment during the shifting of sensory

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experiences, develop a perspective on thoughts and feelings so that they are recognized as mental events rather than as aspects of the self or as necessarily accurate reflections of reality (Teasdale, 1995), and to develop awareness of when one's mind has wandered in order to redirect attention to the present moment. This approach assumes that greater awareness and acceptance of present moment experience will reduce negative affect and improve liveliness and coping ability.

Many researchers have documented the effectiveness of mindfulness in reducing stress and other negative physiological and psychological symptoms, such as pain, illness, and negative affect. Ramel et al. (2004) investigated the effects of an eight-week course in mindfulness-based stress reduction on symptoms of depression and anxiety, dysfunctional attitudes, and rumination in patients with past depression. The researchers found that mindfulness practice is associated with decreased ruminative thinking, a hallmark of many psychological disorders which often prevents patients from taking the right steps to combat their disease due to preoccupation with past experiences. Similarly, Speca et al. (2000) examined the effects of MBSR on mood disturbance and symptoms of stress in cancer outpatients, finding that patients who underwent the MBSR program showed significant reductions in levels of depression and anxiety, as well as fewer symptoms of stress. Moreover, studies in non-clinical samples have documented the benefits of mindfulness in alleviating stress and anxiety (Astin, 1997; Shapiro et al., 1998). For example, Shapiro et al. (1998) assessed the short-term effects of MBSR on premedical and medical students, finding that individuals who engaged in the mindfulness intervention reported reduced state and trait anxiety and overall psychological distress.

Similarly, mindfulness-based cognitive therapy has been used as a form of psychotherapy to aid patients who suffer from various psychological disorders such as depression and anxiety. MBCT combines mindfulness training with cognitive behavioral therapy (CBT), a type of

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psychotherapy which focuses on the relationships between thoughts, feelings, and behaviors, and strives to modify maladaptive patterns of thinking to improve coping (Kabat-Zinn, 1990). Like MBSR, MBCT is typically an eight-week program which teaches patients to recognize and disengage from negative, ruminative thinking and to access a more favorable mode of thinking characterized by awareness and acceptance (Segal et al., 2002). MBCT has been shown to be particularly effective in reducing anxiety and mood symptoms (Evans, Ferrando, Findler, Stowell, Smart, & Haglin, 2008; Semple, 2005; Teasdale et al., 2000; Kuyken et al., 2008). For example, Teasdale et al. (2000) evaluated the effect of MBCT on recurrently depressed patients in an effort to decrease the depressive thinking which often contributes to relapse. They found that MBCT significantly reduced the risk of relapse in patients with three or more previous episodes of depression, demonstrating the psychological benefits that mindfulness can have on mental health. Kuyken et al. (2008) found similar beneficial effects of mindfulness in patients with recurrent depression; in particular, that MBCT was more effective than antidepressant medication in reducing depressive symptoms and psychiatric comorbidity, improving mental and physical well-being, and reducing relapse rates at the fifteen-month follow-up.

Together, these studies indicate that the techniques of mindfulness meditation, with their emphasis on awareness and acceptance of the present moment, represent a powerful coping strategy for individuals who suffer from physical and/or psychological problems. By redirecting awareness from rumination over past experiences to attentiveness to and acceptance of the present moment, mindfulness practice can alleviate stress and negative symptoms associated with many physical and psychological disorders as well as transform the ways in which people respond to negative life events. Nonetheless, while these studies document the beneficial effects of mindfulness on mental and physical health, they do not address the underlying brain

mechanisms involved in this effect. Understanding how mindfulness affects the brain's response to negative life events is necessary for researchers and clinicians to develop the best programs possible for patients who suffer from various mental and physical health problems.

### *Mindfulness and Executive Control*

In addition to improving aspects of physical and mental health, mindfulness meditation has been associated with improved executive functions. Since a key element of mindfulness meditation is engaging in intentional regulation of attentional processes, research has focused on the influence of mindfulness on various aspects of executive control, such as attention. Executive functions are typically carried out by the prefrontal cortex, specifically in the anterior cingulate cortex and dorso-lateral prefrontal cortex. They include higher-order cognitive abilities that facilitate the flexible modification of thought and behavior in the face of new cognitive or environmental demands, and include abilities such as problem solving, planning, decision making, attention, and working memory (Banich & Compton, 2010).

Various researchers have documented the beneficial effects of mindfulness meditation on conflict monitoring, a mechanism of cognitive control in which the brain detects conflicts in information processing and signaling when increased top-down control is required (Botvinick, Cohen, & Carter, 2004). For example, a longitudinal study showed that five days of integrative body-mind training (IBMT) led to improved conflict monitoring (Tang et al., 2007). Subjects showed greater improvement in conflict scores on the Attention Network Test (ANT), a test used to measure the efficiency of the three basic domains of attention: alerting, orienting, and conflict resolution. Additionally, a cross-sectional study revealed that mindfulness meditation for three months resulted in reduced attentional blink (Slagter et al., 2007), a phenomenon related to executive attention that involves a lapse in attention following a stimulus within a rapid serial

visual presentation. Another cross-sectional study found that experienced meditators showed better performance in conflict monitoring as indicated by scores on the ATN (Van den Hurk, Giommi, Gielen, Speckens, & Barendregt, 2010).

Mindfulness meditation has also been studied with respect to the regulation of attention. Mindfulness training is typically associated with concentrative or selective attention. This form of attention is associated with the ability to detect when the mind wanders and redirect attention in order to maintain an understanding of the course of changing thoughts and feelings as well as their triggers and consequences (Lutz, Slagter, Dunne, & Davidson, 2008). This aspect of attention is often what troubles patients with psychiatric disorders such as depression and anxiety, as they have trouble focusing on the present moment and instead ruminate on negative past experiences or fears about the future. Studies have shown that mindfulness enhances the ability to remove unwanted stimuli from attention in order to focus attention on the stimuli or task at hand (Polak, 2009; Jha et al., 2007). Jha et al. (2007) investigated changes in selective attention following mindfulness training, comparing novice meditators who participated in an eight-week MBSR course to experienced meditators who participated in a 1-month intensive mindfulness retreat and a control group. Novice meditators showed improved selective attention as compared to experienced meditators and the control group. Similarly, Jensen et al. (2012) compared healthy meditation novices who participated in MBSR to individuals participating in non-mindfulness stress reduction (NMSR) and a control group. The researchers found that selective attention improved significantly more in the MBSR group, and those in the MBSR group showed less perceived physiological stress and improvements in working memory capacity.

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Mindfulness meditation has also been examined with respect to sustained attention, which is the ability to direct and focus cognitive activity on specific stimuli for the duration of a cognitive task. Overall, studies have shown that mindfulness enhances the ability to sustain attention on a particular task. Chambers et al. (2007), for example, evaluated the impact of an intensive period of mindfulness meditation training on cognitive function in novice meditators. The researchers found that those who participated in a ten-day intensive mindfulness meditation retreat showed increased performance measures of working memory and sustained attention, as well as improvements in self-reported mindfulness, depressive symptoms, and rumination. Additionally, researchers have found that meditators show significantly greater performance than non-meditators in tasks involving sustained attention. Valentine and Sweet (1999) compared the performance of long-term meditators with short-term meditators on a test of sustained attention, the Wilkins' counting test, which requires participants to count the number of random-interval auditory beeps that they hear in a given series. The researchers found that meditators performed significantly better than non-meditators on the task, and that long-term meditators were superior to short-term meditators.

Furthermore, research has documented the beneficial effects of mindfulness on other executive and attentional abilities. For example, Howells et al. (2012) studied the effects of MBCT on aspects of attention in patients with bipolar disorder, finding that bipolar individuals who underwent the MBCT intervention showed improved attentional readiness and attenuated activation of non-relevant information processing during attentional processes. Moore et al. (2009) investigated the link between meditation, self-reported mindfulness, cognitive flexibility, and other attentional functions, comparing a group of experienced meditators with novice meditators on the Stroop test. The researchers found that meditators performed better than non-

meditators on all measures of attention, and that attentional performance and cognitive flexibility were positively correlated with meditation practice and levels of mindfulness. In a follow-up study, Moore et al. (2012) conducted a longitudinal study examining the effects of brief mindfulness training on attentional control, finding that meditation practice improved the focusing of attentional resources during the Stroop test. Additionally, other researchers have found that brief mindfulness meditation training can enhance working memory and the ability to sustain attention (Zeidan et al., 2010; Tang et al., 2007).

Overall, these studies indicate that mindfulness meditation may contribute to attentional improvements and better overall executive function. Meditators showed greater cognitive flexibility as well as better sustained and selective attention, evidencing the beneficial effects of remaining in the present moment, free of ruminative thinking. While we know of many of the brain regions involved in various aspects of executive control, these studies do not provide information about changes in the underlying brain mechanisms that likely occur as a result of the effects of mindfulness when performing cognitive tasks. Examining the underlying neural mechanisms involved in the effects of mindfulness will allow for a better understanding of how mindfulness works to enhance executive function.

### *Mindfulness and Emotion Regulation*

In addition to improving executive control, mindfulness meditation has been associated with enhanced emotion regulation (Lutz et al., 2008; Perlman, Salomons, Davidson, & Lutz, 2010). Emotion regulation involves how individuals influence which emotions they have, when they have them, and how they experience and express them (Gross, 1998). It involves similar aspects of executive control, such as attention, but also entails the changing of cognitions and the modulation of responses (Gross, 1998). Various studies have reported positive effects of

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mindfulness meditation on emotional processing, such as reduced emotional interference by unpleasant stimuli (Ortner et al., 2007), decreased physiological reactivity to stressors (Goleman & Schwartz, 1976), and decreased self-reported difficulties in emotion regulation (Robins, Keng, Ekbal, & Brantley, 2012).

The cornerstone of mindfulness is the ability to attend to all thoughts and emotions in a non-judgmental manner (Kabat-Zinn, 2003), such that one can recognize their emotions without getting caught up in them. Mindful emotion regulation works by strengthening cognitive control mechanisms in brain regions related to affective processing, and this is thought to occur through the present-moment awareness and non-judgmental acceptance associated with mindfulness meditation (Chiesa, Serretti, & Jakobsen, 2013). Researchers have found that emotion regulation processes involve similar brain regions as processes of executive control, including the prefrontal and anterior cingulate cortices (Scherer, Schorr, & Johnstone, 2001). For instance, the ability to regulate emotions seems to be impaired in various mood and psychological disorders, evidenced by decreased connectivity between these brain regions and certain limbic regions important in emotion regulation (Johnstone, van Reekum, Urry, Kalin, & Davidson, 2007).

Mindfulness has been associated with reduced emotional reactions (Ortner, Kilner, & Zelazo, 2007) and healthy emotional functioning (Brown, Goodman, & Inzlicht, 2012). Ortner et al. (2007) found that mindfulness meditation training reduced skin conductance responses to both pleasant and unpleasant images, corroborating the beneficial effects that mindfulness has on the ability to regulate emotional responses. Similarly, Brown et al. (2012) used EEG to study whether individual differences in trait mindfulness would affect neural responses associated with the emotional processing of affective stimuli, especially highly arousing images. The researchers examined the late positive potential (LPP), which is thought to reflect sustained attention to

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emotional stimuli and has been observed to be larger (more positive) for emotionally salient stimuli (Olafsson, Nordin, Sequeira, & Polich, 2008). The researchers found that more mindful individuals showed lower LPP responses to high arousal unpleasant images, indicating that the LPP functions as a neural marker for emotion regulation and that mindfulness can modulate the early phase of emotional processing. More importantly, their findings provide further insight into how mindfulness may operate as an attentional mechanism that aids in regulating emotions to promote healthy emotional functioning, as mindfulness appears to reduce the emotional response following affective stimuli (Brown et al., 2012).

Furthermore, researchers have found that mindfulness meditation can alleviate some of the problems associated with the ruminative thinking characteristic of many psychological disorders such as depression and anxiety. Rumination refers to the tendency to repetitively think about the causes, situational factors, feelings about, and consequences of one's negative emotional experience (Nolen-Hoeksema, 1991). Mindfulness encourages the cultivation of attention to present moment sensation and discourages the evaluative cognitive processes often involved in negative responses to stimuli or experiences. As previously mentioned, Ramel et al. (2004) found that mindfulness helps reduce cognitive rumination, an ability that is essential for people who struggle to regulate and cope with their emotions.

It is important to note, however, that this enhanced ability to regulate emotions due to mindfulness meditation is a result of directing attention to present moment sensation, rather than inhibiting or suppressing cognitive processes through avoidance. Farb et al. (2007) examined the effects of mindfulness meditation training on two distinct forms of self-awareness: the self across time and in the present moment. Using fMRI, the researchers found that attention focused on the present moment via mindfulness meditation training was associated with reductions in midline

cortical activation, areas associated with representations of the self (Kelley, Macrae, Wyland, Caglar, Inati, & Heatherton, 2002), and increased activation of a right-lateralized network in the insula and secondary somatosensory cortices, which have been implicated in detached and objective awareness (Craig, 2002). These findings suggest that mindfulness enhances our ability to become detached from our thoughts and feelings while maintaining awareness of them. This ability is an important aspect of emotion regulation, as it promotes healthy emotional functioning through emphasis on being aware of one's thoughts and feelings in a detached, non-ruminative manner.

Furthermore, emotion regulation seems to be tied to performance and error monitoring, abilities which are essential for healthy mental and emotional well-being. Compton et al. (2008) investigated whether differences in error-related self-regulation predict emotion regulation in daily life. The researchers found that participants higher in cognitive control were better able to regulate their emotions and were less reactive to daily stressors, and attributed these results to the notion that "cognitive control and emotion regulation depend on common or interacting systems" (Compton et al., 2008). Therefore, the beneficial effects of mindfulness on executive function and emotion regulation may not be independent effects. Executive control and emotion regulation may rely upon overlapping cognitive processes, a finding which could aid researchers and clinicians in developing effective forms of therapy for patients who struggle with emotion regulation and/or executive function.

Taken together, this research documents the link between mindfulness and emotion regulation, suggesting that mindful individuals may be more effective at regulating their emotional responses to external stimuli. The emphasis on present moment awareness in mindfulness seems to allow individuals to better regulate their emotions and engage less in

ruminative thinking patterns, which can perpetuate many psychological and mood disorders.

Moreover, the ability to regulate emotional responses seems to be tied to executive function, an important implication which will aid in the understanding of how people react to negative stimuli or events, such as errors.

### *Mindfulness and the Brain*

In parallel to research examining the beneficial effects of mindfulness on psychological well-being and executive function, a second line of research has focused on investigating the brain morphometry and neurophysiological processes related to mindfulness meditation. In particular, researchers have used several biological measures to understand the neural processes underlying the nature of mindfulness and its applications to mental and physical health, including functional magnetic resonance imaging (fMRI) and electroencephalogram (EEG). Since mindfulness affects executive function and emotion regulation, processes which occur in the brain, it must be affecting the physiology of the brain in some way, as brain function and structure are typically linked. By understanding the effects of mindfulness on the physiology of the brain and how this relates to the function of various brain regions, researchers can better understand the underlying beneficial effects of mindfulness.

A significant amount of research has focused on the relationship of mindfulness and the anterior cingulate cortex (ACC), a region of the brain important in executive attention and control (Botvinick, Cohen, & Carter, 2004). The ACC allows us to modify our current behavior in order to achieve a desired goal, a process that is relevant to mindfulness. For instance, studies have shown that patients who struggle with ruminative thinking benefit from mindfulness meditation (Ramel et al., 2004), allowing patients to achieve non-judgmental, mindful awareness

and acceptance. Thus, the ACC can facilitate the modification of one's current ruminative behavior in order to attain the desired mindful behavior.

The majority of the research focusing on the effects of mindfulness on the ACC has found that mindfulness is associated with increased activation of the ACC (Holzel, et al., 2007; Tang & Posner, 2009; Xue, Tang, & Posner, 2011). For example, Xue et al. (2011) found that short-term integrative body-mind training (IBMT), a form of meditation training, has positive effects on brain structure and function in the ACC, as those who engaged in IBMT showed a significant increase in the activity and connectivity of the ACC. Similarly, Tang et al. (2009) found that IBMT was associated with stronger ACC activity, and thus, better self-regulation. Additionally, Davidson et al. (2003) studied the effects of a MBSR intervention on brain function, finding that MBSR subjects displayed significant increases in left-sided activation of the ACC, which has been associated with dispositional positive affect. This suggests that mindfulness training can lead to beneficial changes in the brain in the face of negative stressors.

In addition to studying the anterior cingulate cortex in relation to mindfulness meditation, researchers have looked at other brain regions that appear to be implicated in the underlying effects of mindfulness. Creswell et al. (2007) examined the effects of trait mindfulness on neural regulation of affect during an affect labeling task, finding that dispositional mindfulness was associated with greater activation in the prefrontal cortex and reduced activation in the amygdala. Howells et al. (2012) investigated the effects of MBCT on patients with bipolar disorder using EEG during resting states and completion of a performance task. The researchers found that, compared to control participants, patients with bipolar disorder showed decreased activation of non-relevant information processing during attentional processes, as indexed by improvement over the right frontal cortex and decreased beta band power. Thus, the mindfulness intervention

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improved attentional readiness and attenuated brain activation of non-relevant information processing (Howells, Ives-Deliperi, Horn, & Stein, 2012). Moreover, one fMRI study found that, with increased meditation time, individuals show increased activity in brain regions related to attention, in particular the dorsolateral prefrontal cortex (Lazar et al., 2000).

Additionally, while various studies have examined the neural changes associated with the beneficial effects of mindfulness on clinical symptoms, attention, and emotion regulation, some research has examined the neural changes associated with these effects. For example, mindfulness training appears to effect longer-term structural changes in brain regions associated with emotion regulation. In longitudinal studies, researchers observed gray matter changes following a mindfulness training intervention in certain brain regions, such as increased hippocampal and posterior attention network volume (Holzel et al., 2011), as well as decreased amygdala gray matter volume correlated with reductions in stress following a mindfulness intervention (Holzel et al., 2010). These structural changes in the brain suggest that mindfulness meditation training may increase the habitual ability for encoding momentary experience while decreasing the propensity to attend to emotionally arousing stimuli (Farb, Anderson, & Segal, 2012), which often leads to negative and ruminative thinking. Thus, mindfulness meditation appears to enhance the brain regions associated with emotion regulation, and direct the mind towards a more adaptive and less evaluative way of thinking.

While there is considerable research on the effects of mindfulness meditation and trait mindfulness on the brain, there is some discrepancy among the results. Nevertheless, neuroimaging and EEG results are beginning to demonstrate some consistency regarding the effect that mindfulness has on the brain. In particular, the prefrontal and anterior cingulate cortex appear to be involved in the underlying process of mindfulness, and these brain regions have also

been implicated in executive control and emotion regulation. Therefore, it appears that the areas of the brain related to mindfulness meditation also play important roles in aspects of executive control, such as attention and performance monitoring, as well as emotion regulation. However, research is lacking in detail regarding the precise role of these brain regions, such as the ACC, in executive control. One of the best ways that researchers have begun to study this is with ERP methods, as several studies have found certain event-related potentials to be prominent during tasks assessing executive control, in particular performance monitoring.

### *Mindfulness and Neural Correlates of Performance Monitoring*

Research has documented the positive effects of mindfulness meditation on various aspects of executive control. In particular, researchers have been interested in examining error-related cognitive processing as part of the brain's self-regulatory system, as the ability to notice and respond appropriately to mistakes and negative outcomes can improve future performance and aid in our understanding of the disruptions in self-regulation in various clinical conditions (Compton, Bissey, & Worby-Selim, 2014). However, there has been less research devoted to the understanding of the neural mechanisms underlying this effect. In the past decade, several researchers have examined the effects of mindfulness meditation on behavioral and electrophysiological correlates of executive control and, in particular, performance monitoring in the moments following error commission. The majority of the research has documented the beneficial effects of mindfulness, finding that mindfulness meditation enhances the ability to monitor performance for conflict and errors, as indexed by specific neural correlates of performance monitoring and error-processing.

The particular ERP components that have been studied in relation to performance monitoring that we are interested in are the error-related negativity (ERN), error positivity (Pe),

and error-related alpha suppression (ERAS). The ERN, Pe, and ERAS are neural correlates of performance monitoring and executive control. However, they occur at different times in the error-processing sequence, thus leading researchers to believe that these neural correlates represent different aspects of performance monitoring and our response to errors.

In order to understand the brain's response to errors, we used electroencephalogram (EEG) to record the brain activity of participants. EEG is used to record electrical activity from the brain at the scalp and allows researchers to observe human brain activity that reflects specific cognitive processes. In particular, it records the electrical activity of event-related potentials (ERPs), which are very small voltages generated in the brain in response to specific sensory, motor, and cognitive events or stimuli (Blackwood & Muir, 1990). ERPs can be further subdivided into ERP components, which are time-locked structural features of the ERP. These components reflect one, or more, information processing operations which allow researchers to study neurophysiological correlates of mental processes in a safe and noninvasive manner. ERP components are quantified by their amplitude and frequency. Amplitude refers to the extent to which an information-processing operation is engaged, whereas latency indicates the rate of processing (Luck, 2005).

*Mindfulness and ERN:* One of the neural correlates of performance monitoring and executive control is the error-related negativity (ERN). The ERN is an event-related potential that occurs as a negative deflection in the frontal and central regions of the brain, peaking 60-100 ms after the commission of an error (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). It is generated in the anterior cingulate cortex, which is implicated in cognitive control functions such as performance monitoring and attentional focus, and is thus thought to reflect a process in evaluating the need for control following the commission of an error (Gehring, 2011). Many

theories exist regarding the functional significance of the ERN, including the detection of conflicting response stimuli, a reinforcement learning signal, and an affective response to mistakes (Gehring, 2011). Though the functional significance of the ERN remains uncertain, research has found that there is a relationship between the ERN and performance monitoring, as this particular ERP component peaks shortly after a person initiates an incorrect response in a cognitive task (Gehring, Goss, Coles, Meyer, & Donchin, 1993). Thus, since previous research has documented the beneficial effects that mindfulness has on various aspects of executive control, such as performance monitoring, researchers have studied the ERN with respect to mindfulness, striving to understand the underlying neural mechanisms involved in the effects that mindfulness has on detection of and response to errors.

Teper and Inzlicht (2013) examined the effect of meditation practice on the brain's executive control function, believing that emotional acceptance and performance monitoring play key roles. While completing the Stroop test, participants' brain activity was recorded using EEG to assess the effects of mindfulness on brain components associated with performance monitoring, in particular the ERN. The researchers found two effects of mindfulness. First, meditation practice was found to be related to better executive control, as meditators, defined as those with at least one year of meditation experience, made fewer errors on the Stroop test than control participants. Second, meditators showed a larger ERN, a neural correlate of error processing, in the anterior cingulate cortex. Teper and Inzlicht (2013) suggested that meditators displayed greater emotional acceptance than controls, which is in line with previous research demonstrating that meditators tend to be expert emotion regulators (Perlman et al., 2010) who are highly aware of their emotions (Segal et al., 2002). Therefore, it is possible that the ERN indexes emotional reactivity, as meditators seem to be able to identify their emotions quickly and

accurately, as indexed by a heightened ERN amplitude shortly after the commission of an error. However, another possibility is that the ERN reflects error detection and that mindfulness enhances this ability to notice errors.

*Mindfulness and Pe:* A second ERP component associated with error-related performance monitoring is the error-positivity (Pe), which occurs in the central-posterior regions of the brain with maximum amplitude between 200-400 ms following the commission of an error. The Pe typically co-occurs with the ERN, and unlike the ERN, only occurs in response to errors. There are several theories about the functional significance of the Pe. Some research suggests that the Pe reflects the conscious processing and awareness of errors (Larson & Perlstein, 2009), while other research suggests that it represents an affective response to an error and the motivational salience of an error (Overbeek et al., 2005).

Similar to the ERN, the Pe has also been studied as a neural correlate of performance monitoring with respect to mindfulness. In addition to examining the effects of mindfulness meditation on the ERN, Teper and Inzlicht (2013) also examined the effects of mindfulness meditation on the Pe, finding that mindfulness participants showed slightly less positive Pe amplitude than the control participants. Additionally, Larson et al. (2013) examined the effects of a mindfulness intervention on executive control, in particular performance monitoring. Participants in the mindfulness group were non-meditators who engaged in a brief mindfulness intervention via Kabat-Zinn's *Mindfulness for Beginners* CD set, which focused on both educating participants on mindfulness and directing participants through brief mindfulness exercises. The mindfulness group was compared to a control group who only listened to educational clips on mindfulness from the same CD. Though there were non-significant

differences between the mindfulness and control groups for ERN amplitude and latency, Pe amplitude was significantly smaller in individuals in the mindfulness group.

Based on these findings, it seems as if the ERN and Pe tap into different aspects of the error-processing sequence. While the ERN has been found to be larger in meditators shortly after the commission of an error, the Pe, which occurs later than the ERN in the error-processing sequence, has been found to be smaller in meditators following the commission of an error. Therefore, the ERN may reflect increased awareness of errors, since meditators show heightened immediate response to errors, while the Pe may reflect increased emotional acceptance of errors, since meditators show a reduced response to errors later in the error-processing sequence.

*Mindfulness and ERAS:* The third ERP component associated with error processing, the error-related alpha suppression (ERAS), reflects changes in the oscillatory activity in the alpha range of EEG, and alpha power has been shown to be attenuated after an error commission (Carp & Compton, 2009). In general, alpha activity reflects a brain wave associated with drowsiness and is inversely related to mental activation (Compton, Hofheimer, & Kazinka, 2013). Thus, suppression of alpha activity is thought to reflect an increase in mental activation and, in relation to performance monitoring, is considered an arousal response to errors. Similar to the ERN and Pe, the functional significance of the ERAS is currently unclear. However, greater ERAS has been associated with increased post-error slowing, negative affect, anxiety, increased cortisol levels, and reduced coping behaviors (Compton et al., 2013). Moreover, the ERAS has been found to be sensitive to motivational factors, as Compton et al. (2014) found that participants showed greater alpha suppression following errors which had greater motivational value. While literature has not come to a clear conclusion on whether ERAS reflects a maladaptive or adaptive process, most research suggests that greater ERAS represents a maladaptive process given its

association with typically negative phenomena. The present study will be the first to examine the influences of a mindfulness meditation induction on ERAS, with the aim of elucidating the functional significance of ERAS.

No prior research which examines the effect of mindfulness on error-related alpha suppression (ERAS) exists, though few studies have implicated the ERAS in performance monitoring and error processing. Carp and Compton (2009) investigated the effect of errors on cortical arousal, indexed by changes in EEG alpha band power. Overall, the researchers found that participants elicited less alpha power following errors than correct responses, suggesting that the ERAS may represent an arousal response to errors. Whereas alpha power followed a quadratic trend after correct responses, which the researchers believed to be an indication of mental disengagement from the task during the intertrial intervals, this quadratic trend was absent following errors. The researchers suggested that this decrease in alpha power following the commission of an error represents increased arousal and mental alertness during the intertrial interval, thus evidencing the role that the ERAS plays in error-processing. In addition, Compton et al. (2013) examined the relationship between error-related ERPs and cortisol reactivity, finding that participants with more pronounced ERNs exhibited less cortisol increase during the cognitive task, and that participants with greater ERAS showed greater cortisol increase during the cognitive task. The researchers suggested that more pronounced ERNs may indicate an adaptive response to errors, as it may indicate better stress regulation during the task, while an enhanced ERAS following an error may represent a maladaptive arousal response to errors.

Based on these findings, it appears that mindfulness is associated with increased conscious awareness of errors, as indexed by a larger ERN amplitude (which occurs shortly after the commission of an error) in meditators (Teper and Inzlicht, 2013), as well as increased

emotional acceptance following the commission of an error, as indexed by a smaller Pe amplitude (which occurs later in the error-processing sequence) in meditators (Larson et al., 2013). The research suggests that meditators show heightened immediate response to errors, demonstrating increased awareness during performance monitoring, but subsequently show increased emotional acceptance to their errors, as meditators may lend less attention to their errors or find their errors less motivationally salient. Despite these findings, the reasoning behind the current evidence remains elusive, as researchers are still unclear about how the neural effects of mindfulness are connected to various aspects of executive function. Therefore, further research is needed in order to understand the brain processes invoked during error-processing under the effects of mindfulness.

### Present Study

The present study aims to elucidate the effects of a mindfulness induction on the ERN and Pe, and is the first to examine the effects of mindfulness on the ERAS, with the intention of better understanding the neural mechanisms underlying the beneficial effects of mindfulness with relation to performance monitoring. Teper and Inzlicht (2013) investigated the effect of meditation practice on the underlying mechanisms in the brain that have been implicated in executive control, in particular the ERN, finding that meditators showed a larger ERN and exhibited greater executive control (fewer errors) than control participants. In addition, Larson et al. (2013) found that the amplitude of the Pe was significantly smaller in individuals who received the mindfulness intervention as compared to those in the control condition.

Based on previous research, it seems that the ERN and Pe represent different aspects of the performance monitoring process, as the effect of mindfulness on these two neural correlates of performance monitoring go in opposite directions. These studies show that mindfulness may

increase initial detection of an error, as indexed by a larger ERN amplitude, yet decrease subsequent arousal and motivational salience of an error, as indexed by a smaller Pe amplitude. Therefore, given the implication of the ERN and Pe in executive control and performance monitoring, we intended to provide further evidence in support of the role that the ERN and Pe play in performance monitoring and executive control.

Moreover, we investigated the role of the ERAS in performance monitoring, as there is no prior research on the effects of a mindfulness induction on the ERAS. Evidence suggests that alpha power is reduced following errors (Carp & Compton, 2009; Compton, Arnstein, Freedman, Dainer-Best, & Liss, 2011), and that alpha power reductions are correlated with increased arousal and negative emotions and outcomes (Sobotka, Davidson, & Senulis, 1992; Papousek, Weiss, Schulter, Fink, Reiser, & Lackner, 2014). Given these findings, it appears that the ERAS may represent a maladaptive response to errors. Therefore, we predicted the ERAS to be reduced following errors for those in the mindfulness condition. A reduced ERAS following a mindfulness induction may reflect an acceptance of errors, serving as an indicator of the acceptance aspect of mindfulness.

The present study replicated the procedure that Larson et al. (2013) employed, as we used the same mindfulness induction to investigate the neural correlates of performance monitoring. However, in addition to examining the ERN and Pe with respect to mindfulness, we also examined the difference in alpha power across conditions in attempt to provide further evidence of the neural correlates of performance monitoring and how they may differ at various stages in the error monitoring sequence in the brain.

In line with previous research, we made several predictions about how a mindfulness induction will influence behavior and the neural correlates of performance monitoring. First, we

predicted that participants exposed to a mindfulness induction will show improved accuracy and reduced reaction times on the Stroop test, as compared to participants in the control condition who did not receive the mindfulness induction. We based these predictions on previous research which has shown that novice meditators show improved performance and greater efficiency on the Stroop test after engaging in meditation exercises (Wenk-Sormaz, 2005; Chan and Woollacott, 2007; Teper & Inzlicht, 2013).

Next, we predicted that participants exposed to a mindfulness induction will have a larger ERN amplitude, a smaller Pe amplitude, and a reduced ERAS following the commission of an error, as compared to participants in the control condition. We based our ERP predictions on previous research which found that those who engage in a mindfulness induction show an increased ERN amplitude (Teper & Inzlicht, 2013) but a smaller Pe amplitude (Larson et al., 2013) following the commission of an error. We based these predictions on the idea that mindfulness seems to increase momentary awareness of errors, but decreases the subsequent arousal to negative events (Larson et al., 2013). Therefore, we expected the ERN to have an increased (more negative) amplitude since it is a neural marker that occurs shortly after an error has been made, while we expected the Pe to have a decreased (more positive) amplitude since it occurs later in the error processing sequence. Additionally, we predicted the ERAS to be reduced in participants exposed to the mindfulness induction as compared to those in the control condition, as the ERAS is observed later in the error processing sequence and has been found to reflect an arousal response to errors.

### Methods

#### *Participants*

We recruited 37 students (10 males, 27 females) from Haverford College to participate for compensation of \$20.00. Participants were selected based on a pre-screening questionnaire, which consisted of the 39-item version of the Five Facet Mindfulness Questionnaire (Baer, Smith, Hopkins, Krietemeyer, & Toney, 2006) assessing trait mindfulness, and the 16-item Penn State Worry Questionnaire (Meyer, Miller, Metzger, & Borkovec, 1990) assessing levels of worry. We used the awareness factor of the Five Facet Mindfulness Questionnaire when sorting participants into groups, as this factor best reflected the mindful awareness aspect of mindfulness. The awareness scale consisted of items such as “when I do things, my mind wanders off and I am easily distracted” and “it seems I am running on automatic without much awareness of what I’m doing.” The other subscales of the FFMQ were not further examined for purposes of the present study. The awareness factor of the FFMQ was used to balance the groups in the present study, where half of each group (experimental and control) was pre-selected to be more mindful, and half of each group was preselected to be less mindful. The pre-screening questionnaire also contained various demographic questions, such as age and gender.

Three participants were excluded from the mindfulness condition, and one participant was excluded from the control condition. Two participants were excluded due to high error rate on the Stroop test, one participant was excluded due to poor quality data from two sites, and another participant was excluded due to technical difficulties. Thus, data analysis was conducted on 33 participants (10 males, 23 females), with 18 participants in the control condition (4 males, 14 females) and 15 participants in the mindfulness condition (6 males, 9 females). Furthermore, exploratory analysis revealed no effects of gender on ERN amplitude, Pe amplitude, log alpha power, or any of the individual differences variables.

### *Design*

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The study includes one independent variable, condition, with two between-subjects groups: the control group (no mindfulness induction), and the mindfulness group (mindfulness induction). The dependent variables included ERN amplitude, Pe amplitude, log alpha power, trial accuracy, and reaction time. Average ERN amplitudes, Pe amplitudes, and log alpha power for each group were calculated for error and correct trials to measure differences in the ERN, Pe, and alpha power depending on group. Reaction time and accuracy were calculated for congruent, neutral, and incongruent trials of the Stroop test and used to measure Stroop interference.

### *Procedure*

During the study, participants came to the lab individually and upon entering immediately received the informed consent form. After completing this form, participants were fitted with the EEG cap, which was used to record brain activity during the Stroop test. Once the electrode cap was in place, the participant was seated in the experimental room and the experimenter ensured that the EEG equipment was functioning correctly, impedances were low, and the data was recording correctly. Next, participants listened to the audio clips on mindfulness, depending on which condition they were in. Those in the experimental condition listened to an educational clip on mindfulness as well as a mindfulness exercise on breathing. Those in the control condition listened to two educational clips on mindfulness. Then, participants filled out a self-report questionnaire on the computer, the 20-item state version of the *State-Trait Anxiety Inventory* (Spielberger, 1983), which assesses state anxiety. Finally, participants completed the behavioral task, the Stroop test. Immediately following the completion of the Stroop test, participants completed a short questionnaire indicating their level of previous mindfulness experience on a scale of one to ten, and were asked to provide a short explanation about their previous mindfulness experience.

### *The Mindfulness Induction*

Participants in both the experimental and control conditions listened to clips on mindfulness from Jon Kabat-Zinn's *Mindfulness for Beginners* (Kabat-Zinn, 2006) CD set, given its success as an induction in previous studies on mindfulness and cognitive control (Larson et al., 2013). Participants in the mindfulness condition listened to a short clip to educate them on mindfulness meditation, and subsequently engaged in a *Mindfulness of Breathing* audio exercise which focused on attending to one's breathing and being mindful in the present moment.

Participants in the control condition listened to two educational clips on mindfulness, including *Awareness, a Sixth Sense*, which focused on environmental awareness, and *An Ethical Foundation*, which focused on ethical behaviors. These two clips did not involve any meditation practice. Therefore, all participants listened to clips from the same CD with the same voice for approximately fourteen minutes. The only difference between the two conditions was that the mindfulness group participated in mindfulness meditation exercises and therefore received a brief mindfulness induction, whereas the control group did not actively participate in any mindfulness meditation exercises.

### *The Stroop Test*

The Stroop test has been used in previous research as a measure of executive control, as it is used to elicit performance errors. It is a test measuring attentional functioning by requiring participants to ignore their habitual process of word reading in order to attend to the color that the word is displayed in, which is a less automatic task. Participants completed a six-choice Stroop test modeled after Compton et al. (2008) on a Dell desktop computer running E-prime software. The task required participants to identify the color of the target word using the first three fingers of each hand. The six color responses were red, orange, yellow, green, blue, and

purple, mapped onto the fingers from left to right. Stimulus words were either a color word, from the options of the above colors such as “RED,” or were a simple, unrelated word such as “DOG.” There were congruent trials, when the stimulus word and the color of the font of the word matched, incongruent trials, when they did not match, and neutral trials, when a non-color word was used.

The task began with a practice block of 24 trials. Accuracy feedback was given after each practice trial, but not during the main trial blocks. The main experiment included 8 blocks of 90 trials per block (720 total trials). Each block included 30 incongruent trials (*e.g.*, “blue” in red font), 30 neutral trials (*e.g.*, “cat” in red font), and 30 congruent trials (*e.g.*, “green” in green font) in a randomly intermixed order. Each trial event included a 150-ms presentation of the target word against a black background, followed by a blank screen that remained present until a key press or for a maximum duration of 2000 ms. A blank screen was presented for 1280 ms following the key press until the onset of the next stimulus. When a participant failed to respond in the allotted time, these responses were characterized as “no responses” and were thus excluded from data analysis.

### *Electrophysiological Recording*

Electrodes were applied using an elastic cap (Quik-Caps) fitted with sintered Ag/AgCl electrodes. Data was recorded continuously from ten scalp sites (Fz, FCz, Cz, Pz, F3, F4, C3, C4, P3, P4). Signals were amplified by a NuAmps amplifier controlled by Neuroscan software, with a sampling rate of 1000 Hz and a bandpass of 0.1-40 Hz (-3dB). Data was referenced on-line to the right mastoid and digitally re-referenced off-line to the average of left and right mastoids. Eye movements were monitored by electrodes placed above and below the left eye and at the

canthus of each eye. Recordings from these four sites were used to compute bipolar horizontal and vertical EOG channels off-line.

Artifacts were addressed off-line in three steps. First, upon visual inspection, portions of the EEG record with large non-blink artifacts were manually excluded. Second, the effect of blinks were reduced using the Neuroscan software's regression-based algorithm for ocular artifact reduction. Third, remaining artifacts in the EEG were identified using a  $\pm 150 \mu\text{v}$  threshold, and corresponding epochs were excluded. Following baseline correction, response-locked signal averaging were carried out separately for correct and error trials.

To analyze the ERN and Pe, continuous data was segmented into epochs beginning 200 ms before the button press and ending 600 ms after it. Baseline correction was applied using values in the -200 to -100 ms window to define the baseline. Segments were averaged separately for correct and error trials. In the resulting ERPs, the ERN peak was defined as the most negative amplitude between -50 and 100 ms after the button press. Within the same ERP waveforms, the Pe was defined as the peak value between 100 and 300 ms after the button press.

The methods for analyzing alpha power were modeled after Compton et al. (2014). To analyze alpha power, each intertrial interval, lasting a total of 1,280 ms, was divided into five epochs each lasting 256 ms. The fast Fourier transform was used to calculate power spectra for each epoch. Spectra for each epoch were then averaged separately for error and correct trial types. Statistical analyses were conducted using log-transformed mean power values in the 10-14 Hz frequency band.

### Results

#### *Self-Reported Individual Differences Data*

An independent samples t-test was used to determine whether the conditions differed with respect to several individual differences measures. There was no significant difference between conditions with respect to STAI score,  $t(31) = -.761, p = .453$ , and mindfulness experience level,  $t(31) = .566, p = .575$ , indicating that the conditions did not differ with respect to anxiety or previous mindfulness experience. Though we balanced the groups by trait mindfulness so that one group didn't have initially more mindful people than the other, the groups unexpectedly differed by worry level. There was a significant difference between conditions with respect to PSWQ score,  $t(31) = -2.77, p < .01$ , such that PSWQ scores were significantly higher for participants in the control condition ( $M = 54.4, SD = 10.1$ ) relative to participants in the mindfulness condition ( $M = 44.3, SD = 11.0$ ). This indicates that any effect of condition could be due to statistically significant effects of worry.

In addition, a correlational analysis was conducted to examine the relationship between the various individual differences variables. Results from the analysis revealed that PSWQ score and STAI score were significantly positively correlated,  $r = .668, p < .001$ , showing that people who were self-reported worriers at the time of the pre-screening were also more anxious during the session. STAI score was also significantly negatively correlated with the awareness factor,  $r = .378, p = .03$ , indicating that people who self-reported as being more anxious were also characterized as being less aware. Mindfulness experience level was marginally negatively correlated with STAI score,  $r = -.341, p = .052$ , demonstrating that those who self-reported greater mindfulness experience were also somewhat characterized as being less anxious. Moreover, the awareness factor was completely uncorrelated with mindfulness experience level,  $r = .001, p = .996$ .

### *Behavioral Data*

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Two measures of performance were examined to determine differences between conditions in performance on the Stroop test: trial accuracy (proportion correct) and reaction time. To examine the effect of mindfulness on trial accuracy, we carried out a 2 x 3 mixed factorial analysis of variance (ANOVA), with trial type (congruent, incongruent, neutral) as a within-subjects factor and condition (control, mindfulness) as a between-subjects factor. Results of the analysis showed the predicted effect of Stroop interference and thus a main effect of trial type, in which participants were less accurate on incongruent trials than congruent or neutral trials,  $F(2,62) = 14.53, p < .001$ . Accuracy was significantly lower for incongruent trials ( $M = .887, SEM = .02$ ) than congruent ( $M = .916, SEM = .02$ ) or neutral ( $M = .919, SEM = .02$ ) trials, which did not significantly differ from each other (Bonferroni post-hoc test,  $p < .05$ ). Condition, however, did not have an effect on accuracy on the Stroop test, as there was no main effect or significant interaction between condition and trial type,  $F(2,62) = 1.574, p = .215$ . Thus, there was no significant difference between the two groups for accuracy on the Stroop test, indicating that the mindfulness induction did not affect accuracy on the Stroop test.

Reaction time on the Stroop test was also investigated using a 2 x 3 mixed factorial ANOVA, with trial type (congruent, incongruent, neutral) as a within subjects factor and condition (control, mindfulness) as a between-subjects factor. Once again, the predicted effect of Stroop interference, in which participants have slower reaction times for incongruent trials than congruent or neutral trials, was shown in the data, as the main effect of trial type was significant,  $F(2,62) = 111.323, p < .001$ . Reaction times were significantly higher for incongruent trials ( $M = 698, SEM = 24.17$ ) than congruent ( $M = 603, SEM = 20.54$ ) or neutral ( $M = 595, SEM = 20.46$ ) trials, which did not significantly differ from each other (Bonferroni post-hoc test,  $p < .05$ ). However, condition did not have an effect on reaction times on the Stroop test, as there was no

main effect or significant interaction between condition and trial type,  $F(2,62) = .929, p = .4$ .

Thus, the mindfulness induction did not affect reaction times on the Stroop test.

Together, results from the behavioral data suggest that the mindfulness induction did not affect performance on the Stroop test, as the mindfulness and control groups did not differ in trial accuracy or reaction times on the Stroop test. Nonetheless, the results demonstrate that participants displayed the typical effect of Stroop interference, as participants were less accurate and slower for incongruent trials than congruent or neutral trials.

#### *ERN Data*

One event-related potential that was analyzed in this study was the ERN, which is a negative going wave that peaks approximately 100 ms after an incorrect button press during a cognitive task (Gehring, 2011). Figure 1 depicts the grand-average waveforms for correct and error trials for all participants (first peak indicates ERN). ERN data was analyzed using a 2 x 2 x 4 mixed factorial ANOVA, including trial accuracy (error, correct) and electrode site (Fz, FCz, Cz, Pz) as within-subjects factors, and condition (mindfulness, control) as a between-subjects factor.

Results of this analysis showed a significant main effect of accuracy on ERN peak amplitude, such that ERN amplitude was significantly higher (more negative) 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. In order to test the effect of the mindfulness induction on ERN amplitude, the effect of condition was analyzed. There was no significant main effect of condition on ERN amplitude,  $F(1,31) = 2.19, p = .149$ . Moreover, there was no significant interaction between accuracy and condition on ERN

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amplitude,  $F < 1$ . Together, these findings suggest that ERN amplitude was not affected by condition, nor was the mindfulness induction successful in influencing the ERN.

To assess the effect 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 x 2 x 4 mixed factorial ANOVA. The results of this analysis showed a significant three-way interaction between accuracy, site, and awareness,  $F(3,90) = 5.02, p < .03$ . Next, each site was examined separately to determine at which site(s) the awareness factor effects the ERN. The results of this analysis showed that the interaction between accuracy, site, and awareness was driven by the accuracy x awareness interaction at the Pz site,  $F(1,30) = 9.9, p < .005$ , and was not significant at the FCz, Cz, and Fz sites. Furthermore, to examine the direction of the accuracy x awareness interaction at the Pz site, a correlational analysis was conducted, where ERN amplitude at the Pz site was calculated through a difference score of correct minus error trials and then correlated with awareness. Results of this correlational analysis showed that there was a significant negative correlation between ERN amplitude at the Pz site and the awareness factor,  $r = .503, p < .005$ , indicating that the ERN at the Pz site was larger for people with a lower awareness score.

To assess the effect of state anxiety on ERN amplitude, an STAI score factor (sum of items from STAI questionnaire) was introduced as a co-variate into the previously described 2 x 2 x 4 mixed factorial ANOVA. The results of this analysis showed a significant interaction between accuracy and STAI,  $F(1,30) = 5.01, p < .05$ . Likewise, in a separate analysis, self-reported mindfulness experience was introduced as a co-variate into the ANOVA. The results of this analysis showed a significant three-way interaction between accuracy, site, and mindfulness experience level on ERN amplitude,  $F(3,90) = 4.40, p < .03$ . There was also a significant main

effect of mindfulness experience level on ERN amplitude,  $F(1,30) = 8.78, p = .006$ . The PSWQ score was introduced as a co-variate, but there were no significant effects involving PSWQ.

Lastly, to assess the direction of the relationship between the individual differences measures and ERN amplitude, a correlation was conducted between ERN amplitude at all four sites (correct minus error trials), STAI score, and mindfulness experience level. Results from this analysis showed that STAI score correlated positively with ERN amplitude,  $r = .357, p < .05$ , while mindfulness experience level correlated negatively with ERN amplitude,  $r = -.380, p < .03$ . This indicates that those who had higher self-reported levels of anxiety displayed a greater ERN, and those who self-reported having more mindfulness experience displayed a smaller ERN.

Together, results from the ERN data suggest that the mindfulness induction had no effect on ERN amplitude, but various measures of individual differences predict ERN amplitude, such as awareness, mindfulness experience, and anxiety.

### *Pe Data*

The second event-related potential that was analyzed in this study was the Pe, which is a positive going wave that peaks approximately 200-400 ms after an incorrect button press during a cognitive task (Overbeek et al., 2005). Again, Figure 1 depicts the grand-average waveforms for correct and error trials for all participants (second peak indicates Pe). Pe data was analyzed using a 2 x 2 x 4 mixed factorial ANOVA, including trial accuracy (error, correct) and electrode site (Fz, FCz, Cz, Pz) as within-subjects factors, and condition (mindfulness, control) as a between-subjects factor.

Data analysis revealed a main effect of accuracy on Pe peak amplitude, such that Pe amplitudes were significantly larger following error trials ( $M = 4.91\mu\text{V}, SEM = .565$ ) relative to correct trials ( $M = 1.22\mu\text{V}, SEM = .256$ ) on the Stroop test,  $F(1,31) = 38.23, p < .001$ . This result

confirms the presence of the Pe during the Stroop test. There was no significant main effect of condition, nor a significant interaction between accuracy and condition,  $F < 1$ . Together, these findings suggest that Pe amplitude was not affected by condition, nor was the mindfulness induction successful in influencing the Pe.

Although not relevant to the primary hypotheses, analyses also revealed effects of electrode site, as there was a main effect of site,  $F(3,93) = 5.80, p = .001$ , as well as a significant interaction between site and accuracy,  $F(3,93) = 13.10, p < .001$ , which is shown in Table 1. The means indicate greater Pe amplitude at more posterior sites.

To assess the effect of the four different self-report variables on Pe amplitude, the awareness factor, STAI factor, PSWQ factor, and mindfulness experience factor were introduced separately as co-variates into the previously described 2 x 2 x 4 mixed factorial ANOVA. Results of the analyses showed no significant interaction between Pe amplitude and the awareness factor, or between Pe amplitude and the mindfulness experience factor. However, there was a marginally significant main effect of STAI score on Pe amplitude,  $F(1,30) = 3.66, p = .065$ , indicating that Pe amplitude depended on STAI score notwithstanding correct or error trial differentiation. Furthermore, to examine the effect of worry level on Pe amplitude, the PSWQ score was introduced as a co-variate into the ANOVA. Results from this analysis showed that there was a significant interaction between accuracy and PSWQ score,  $F(1,30) = 8.57, p < .01$ , as well as a significant main effect of PSWQ score on Pe amplitude,  $F(1,30) = 8.16, p < .01$ . A correlational analysis revealed a significant negative correlation between Pe amplitude at all four sites (error minus correct trials) and PSWQ score,  $r = -.383, p < .03$ , indicating that a smaller Pe was predicted by more worrisome participants. Together, these analyses show that the only

individual differences variable that significantly predicted Pe amplitude was worry level from the PSWQ.

Together, results from the Pe data suggest that the mindfulness induction had no effect on Pe amplitude, but the individual difference measure of worry predicts Pe amplitude.

#### *ERAS Data*

To analyze the alpha power data for the ERAS, we used a 2 x 2 x 5 x 9 mixed factorial ANOVA, including trial accuracy (error, correct), electrode site (Fz, F3, F4, Pz, P3, P4, Cz, C3, C4), and epoch window (0-255, 256-511, 512-767, 768-1023, 1024-1279) as within-subject factors, and condition (mindfulness, control) as the between-subjects factor. Results of this analysis showed a significant main effect of accuracy on alpha power in the predicted direction, such that alpha power was significantly smaller following error trials ( $M = 1.42$ ,  $SEM = .052$ ) relative to correct trials ( $M = 1.47$ ,  $SEM = .051$ ) on the Stroop test,  $F(1,31) = 8.27$ ,  $p = .007$ . This result confirms the presence of the ERAS during the Stroop test.

Results of this analysis also showed a marginally significant interaction between accuracy and condition,  $F(1,31) = 3.79$ ,  $p = .06$ . As shown in Table 2, alpha power was marginally smaller following error trials relative to correct trials for those in the mindfulness condition, but there was no significant difference in alpha power following error trials relative to correct trials for those in the control condition. However, there was no significant main effect of condition on alpha power,  $F(1,31) = .254$ ,  $p = .618$ , indicating that condition did not alone affect alpha power. Following the interaction between condition and accuracy, we conducted simple effects analyses to examine the effects of accuracy for each condition separately. Results from these analyses revealed that there was a significant simple main effect of accuracy for the mindfulness condition, as there was a significant difference in alpha power for correct and error

trials,  $F(1,14) = 7.79, p < .05$ . However, there was not a significant simple main effect of accuracy for the control condition,  $F(1,17) = .68, p = .42$ . This suggests that those in the mindfulness condition showed significant error-related alpha suppression effect, whereas those in the control condition did not. Moreover, taken together these results suggest that the mindfulness induction had an effect on alpha suppression, as the effect of trial accuracy was different across conditions. However, this finding was not in the predicted direction, since those in the mindfulness condition displayed higher alpha power following correct trials rather than error trials.

Additionally, there were several results from the analyses that showed significant effects but were not relevant to the main goals of the study. As shown in Table 3, there was a significant main effect of epoch on alpha power,  $F(4,124) = 9.27, p < .001$ , as well as a significant interaction between accuracy and epoch,  $F(4,124) = 20.57, p < .001$ , such that alpha power was significantly different across epoch periods following correct trials, but was not significantly different across epoch periods following error trials. As shown in Table 4, there was a significant main effect of site on alpha power,  $F(8,248) = 12.34, p < .001$ , in which the parietal sites displayed more alpha activity. Also depicted in Table 4 is the significant interaction between accuracy and site,  $F(8,248) = 32.08, p < .001$ , such that alpha power was significantly different across sites following correct trials, but was not significantly different across sites following error trials. Furthermore, results from the analysis showed a significant interaction between epoch and site,  $F(32,992) = 26.64, p < .001$ , as well as a significant interaction between accuracy, site, and epoch,  $F(32,992) = 39.85, p < .001$ . However, these effects are not relevant to the hypotheses and involve a large amount of means, so they are not displayed.

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To assess the effect of the four individual differences variables (STAI score, PSWQ score, awareness factor, and mindfulness experience level) on alpha power, these four variables were introduced separately as co-variates into the previously described 2 x 2 x 5 x 9 mixed factorial ANOVA, but no significant interaction was found between alpha power and any of these four measures of individual differences. Thus, results from the ERAS data suggest that the mindfulness induction had an effect on alpha suppression, but the various individual differences measures were not predictors of ERAS.

### Discussion

The present study was conducted in order to investigate the effect of a mindfulness induction on the brain's response to performance errors. Specifically, we investigated how a brief mindfulness induction would affect performance on a cognitive task and the specific neural correlates of performance monitoring, the error-related negativity (ERN), error positivity (Pe), and error-related alpha suppression (ERAS). Mindfulness was manipulated using a mindfulness induction via a short audio clip on mindfulness. Cognitive control was assessed in terms of performance on a Stroop test (trial accuracy and reaction time), the difference in amplitude of the ERN, the difference in amplitude of the Pe, and the difference in alpha power for the ERAS, for error versus correct trials and between groups. The results revealed that the mindfulness induction somewhat affected the neural correlates of performance monitoring. While the mindfulness induction had no effect on ERN or Pe amplitude, and did not result in diminished performance on the Stroop test, it did result in greater alpha suppression. Moreover, data analysis revealed that the self-reported individual differences measures of anxiety, worry, awareness, and mindfulness experience were predictors of some of the neural correlates of performance monitoring.

This study was created as an extension of the research conducted by Larson et al. (2013) investigating the effects of a brief mindfulness intervention on the amplitude of the ERN and Pe. Several changes to the Larson et al. (2013) study design were implemented in the design of the current study. We examined changes in alpha power to measure the ERAS, which has been shown to be involved in error processing at a later stage than the ERN and Pe. Our inclusion of the ERAS as a dependent variable allowed us to elucidate the effects of a mindfulness induction on a neural correlate of performance monitoring that occurs later in the error-processing sequence and one which has not been examined with respect to a mindfulness induction. Moreover, we used the Penn State Worry Questionnaire as a measure of worry instead of the Beck Depression Inventory, which Larson et al. (2013) used to measure depressive symptoms. We also included the Five Facet Mindfulness Questionnaire assessing various aspects of mindfulness, such as awareness. These changes were included to better examine the relationship between the neural correlates of error-monitoring and individual differences in worry, anxiety, and mindful awareness levels.

Our first hypothesis was that participants exposed to a mindfulness induction would show less Stroop interference than participants in the control group, as measured through reaction time and trial accuracy differences between congruent and neutral versus incongruent trials. The reasoning behind the hypothesized decreased Stroop interference following the mindfulness induction was drawn from research by Teper & Inzlicht (2013), who showed that novice meditators showed improved performance on the Stroop test after engaging in meditation exercises. However, the results of the current study show that the mindfulness induction was not successful in improving performance on the Stroop test. It is possible that the mindfulness manipulation was too short to affect behavioral performance on the cognitive task, as Larson et

al. (2013) similarly found that their mindfulness intervention failed to affect behavioral performance on another cognitive task, the flanker task. However, there was a robust effect of Stroop interference across conditions, showing that the Stroop test measured cognitive control as intended.

Our second hypothesis was that participants exposed to a mindfulness induction would have a larger ERN amplitude following the commission of an error, meaning that there would be a greater difference in the amplitude of the ERN between error and correct trials, as compared to participants in the control condition. The reasoning behind the hypothesized increase in ERN amplitude was drawn from research by Teper and Inzlicht (2013), who found that those who engaged in a mindfulness intervention showed an increased ERN amplitude. However, similar to the results found by Larson et al. (2013), the results of the current study show that the mindfulness induction was not successful in affecting ERN amplitude, as there was no significant difference in ERN amplitude between conditions. Again, it is possible that the mindfulness manipulation was too short to affect ERN amplitude during the cognitive task, or that the absence of differences between groups in ERN amplitude may reflect the naivety of the participants.

Nonetheless, ERN amplitude was correlated with various individual differences measures, as it was negatively correlated with awareness level (albeit only at the Pz site) and mindfulness experience level, and positively correlated with anxiety level (STAI score). The negative correlation between ERN amplitude and awareness level did not reflect our initial prediction that greater awareness would be associated with a larger ERN, as we believed that the awareness factor reflected the “mindful awareness” aspects of the mindfulness induction. Rather, those who self-reported as being less aware showed greater ERN amplitude. However, prior

literature has found mixed results with respect to the association between ERN amplitude and error awareness. For example, Scheffers and Coles (2000) and Band and Kok (2003) found that ERN amplitude increased with growing error awareness during a Flanker and an anti-saccade task. Alternatively, Nieuwenhuis et al. (2001) and Endrass et al. (2005) did not find a difference in ERN amplitude with respect to subjective error awareness during an anti-saccade and a stop-signal task. Therefore, our findings do not seem to replicate the literature which has found that greater error awareness is associated with a larger ERN, nor the literature which has found no relationship between the ERN and error awareness. However, it seems that the items from the awareness factor of the FFMQ addressed other aspects of awareness, such as distractibility, attentiveness, and ability to focus, rather than the awareness of error commission and performance outcomes. Thus, it is possible that a greater ERN is associated with less attentiveness or focus rather than error awareness.

Moreover, ERN amplitude was negatively correlated with mindfulness experience level, which contradicts our initial prediction that a greater ERN would be associated with greater levels of mindfulness. It is possible that those with more mindfulness experience displayed a smaller ERN amplitude due to living in a more relaxed state overall, and thus didn't experience heightened levels of arousal typically associated with the ERN following error commission. Nonetheless, while both the mindfulness experience factor and awareness factor are associated with smaller ERN amplitude, these two variables seem to reflect different aspects of mindfulness, as they were not correlated with each other. The awareness factor may reflect one's propensity or disinclination to remain attentive and focused on the present moment, whereas the mindfulness experience factor may represent one's ability to redirect attention and focus to the

present moment as a result of increased practice or engagement with mindfulness and/or meditation.

Additionally, ERN amplitude was positively correlated with anxiety levels (STAI), and awareness level was negatively correlated with anxiety level. These findings reflect prior literature which suggests that anxiety reflects a negative or maladaptive state, whereas awareness reflects a positive state. The positive association between ERN amplitude and anxiety level reflects prior literature which has found that the ERN is a reliable biomarker of anxiety localized to the ACC (Hajcak, McDonald, & Simons, 2004) and is related to greater negative affect and trait anxiety (Hajcak, 2012; Endrass, Klawohn, Schuster, & Kathmann, 2008; Hajcak et al., 2004). Accordingly, it seems fitting that we found a negative association between ERN amplitude and awareness, as awareness was negatively correlated with anxiety and seems to reflect opposite characteristics of anxiety, such as attentiveness and focus on the present moment.

Our third hypothesis was that participants exposed to a mindfulness induction would show an attenuated Pe following the commission of an error, meaning that there would be less of a difference in the amplitude of the Pe between error and correct trials in participants in the mindfulness condition, as compared to participants in the control condition. The reasoning behind the hypothesized attenuation of Pe amplitude was drawn from research by Larson et al. (2013), who showed that those who engage in a mindfulness intervention show a smaller Pe amplitude. However, the results of the current study show that the mindfulness induction was not successful in affecting Pe amplitude, as there was no significant difference in Pe amplitude between conditions, and thus our results do not replicate the findings of Larson et al. (2013). Similar to our explanation behind the ERN results, it is possible that the mindfulness

manipulation was too short to affect Pe amplitude during the cognitive task, or that the absence of differences between groups in Pe amplitude may reflect the naivety of the participants.

Nonetheless, the individual difference measure of worry (PSWQ score) was significantly negatively correlated with Pe amplitude, suggesting that participants who self-reported as worriers displayed smaller Pe amplitude. This result contradicts what we originally hypothesized, as we believed that more mindful awareness, and thus less worrying, would predict a smaller Pe amplitude. Some lines of literature suggest that greater negative affect and pathological worry is related to increased error-related brain activity (Weinberg, Olvet, & Hajcak, 2010). However, our finding of the negative association between Pe amplitude and worry reflects other lines of literature which suggest that more worry and depressive affect is linked to a smaller Pe (Schroder, Moran, Infantolino, & Moser, 2013), and greater negative affect is associated with a smaller Pe (Hajcak, McDonald, & Simons, 2004).

Lastly, our fourth hypothesis was that participants exposed to a mindfulness induction would show an attenuated ERAS following the commission of an error, meaning that there would be less of a difference in the alpha power between error and correct trials, as compared to participants in the control condition. While the current study is the first study to examine the effects of a mindfulness induction on the ERAS, the reasoning behind the hypothesized attenuation was drawn from previous research by Carp and Compton (2009), who showed that participants elicit less alpha power following errors than correct responses. The researchers argued that the ERAS may reflect an arousal response to errors, since alpha activity reflects a brain wave associated with drowsiness and is inversely related to mental activation (Compton, Hofheimer, & Kazinka, 2013). The results of the current study show that the mindfulness induction was successful in affecting alpha suppression, though not in the direction that we

initially hypothesized, as those in the mindfulness condition displayed greater alpha suppression than those in the control condition.

We initially predicted that those in the mindfulness condition would show attenuated alpha suppression as compared to the control condition. Since previous research suggests that alpha suppression represents a maladaptive arousal response to errors (Carp & Compton, 2009), we predicted that participants in the mindfulness condition would experience greater mindful awareness and less arousal as a result of the mindfulness induction. However, we found that those in the mindfulness condition showed greater alpha suppression, in part due to the fact that alpha power differed significantly following correct trials rather than error trials across conditions. Participants in the mindfulness condition were more relaxed following correct responses as compared to participants in the control condition, yet participants in the mindfulness condition still displayed an arousal response following the commission of an error.

The increased alpha power following correct responses for those in the mindfulness condition reflects some literature which suggests that alpha power is inversely related to mental activation, in that “greater levels of alpha represent synchronization among neuronal firing patterns...and this synchronization is associated with greater disengagement of the cortical structures relative to the given task” (Hatfield & Hillman, 2001). Therefore, participants in the mindfulness condition may have experienced decreased mental activation and greater relaxation following correct trials as compared to error trials. Rather than inducing a state of mindfulness in participants, the mindfulness induction may have simply induced a state of relaxation in participants, especially following correct responses. Thus, the mindfulness induction was unsuccessful in reducing arousal following the commission of an error, but it was successful in influencing alpha suppression in an unexpected way.

Although we found that those in the mindfulness condition showed greater alpha suppression, the mindfulness induction did not affect performance on the Stroop test, suggesting that the ERAS may reflect an arousal response that is not maladaptive. This corresponds to our conception of mindfulness as a good and helpful phenomenon. Despite showing increased alpha suppression, participants in the mindfulness condition performed just as well as participants in the control condition on the Stroop test. Furthermore, regarding the measures of individual differences, awareness, worry, anxiety, and mindfulness experience were not predictive of the ERAS.

There are various strengths and weaknesses of the present study that should be taken into account when evaluating the effectiveness of the study design and manipulation. First and foremost, the present study found many of the expected error effects for the ERN, Pe, and ERAS during the Stroop test, and found that participants were performing on the Stroop task in typical ways. Moreover, in terms of the design of the study, conditions were balanced by gender as well as trait mindfulness, and we modeled the mindfulness manipulation after a previously demonstrated effective manipulation (Larson et al., 2013) on some of the same neural correlates of performance monitoring that we examined.

Despite the various strengths of the present study, there are a few limitations that should be noted. One limitation is that the mindfulness induction was performed in a laboratory setting in a brief time period. The mindfulness induction may have been too short to truly influence any of the neural correlates of performance monitoring as well as performance on the Stroop test. Moreover, it is difficult to truly know whether the mindfulness induction was actually manipulating mindfulness, or whether it was manipulating some other state such as relaxation. Therefore, future studies may want to include a more long-term mindfulness manipulation which

has been shown to be effective in inducing a mindfully aware state in participants. Studies which have used a long-term intervention have demonstrated that mindfulness has positive effects on various aspects of mental and physical health. For example, eight-ten week mindfulness interventions have reduced anxiety and psychological distress (Shapiro et al., 1998) as well of levels of depression and stress (Speca et al., 2000) in participants. While these studies focused more on improving symptoms related to psychological disorders, they demonstrate the effectiveness of a long-term mindfulness intervention, which could prove to also be effective in enhancing performance monitoring.

Lastly, it is unclear whether the self-reported measures of anxiety, worry, awareness, and mindfulness experience were causally related to differences in the neural correlates of performance monitoring, or whether some other factor that we didn't account for affects the relationships between these variables and the neural correlates of performance monitoring. Specifically, future studies should incorporate a measure of relaxation in order to differentiate the mindful awareness and relaxation aspects of the mindfulness induction. Since it was unclear from our results whether or not the mindfulness induction simply induced a state of relaxation or actually induced a state of mindful awareness, future studies should strive to better assess these different aspects of mindfulness through additional individual differences measures.

Overall, we found the mindfulness induction to be somewhat successful in influencing the neural correlates of performance monitoring. While we didn't replicate the findings of prior research which showed that mindfulness is associated with a greater ERN (Teper & Inzlicht, 2013) and a smaller Pe (Larson et al., 2013), we added a new piece to the existing literature on the effects of mindfulness on neural correlates of performance monitoring, as we demonstrated that the mindfulness induction had an effect on alpha suppression (ERAS). Based on these

findings, it is possible that the ERN, Pe, and ERAS reflect different aspects of mindfulness, as the ERAS seems to be more related to the relaxation that occurs as a result of the mindfulness induction, but the ERN and Pe seem to reflect various measures of individual differences such as levels of anxiety, worry, and awareness. Though future research is necessary to fully understand these findings, it seems as if the relaxation that occurred as a result of the mindfulness induction, reflected in the ERAS, doesn't affect the process of error detection that many researchers have found to be reflected in the ERN and Pe. This could be due to the time in which these neural correlates manifest following the commission of an error, as the ERN and Pe peak early in the error-processing sequence, while the ERAS is observed later. Instead of reflecting error detection and performance monitoring, the ERAS may simply reflect the relaxation that occurs after the brain registers its response on a cognitive task.

Moreover, it is interesting that the ERAS was the only neural correlate not related to the trait variables. It is possible that the ERAS is more related to relaxation than anxiety, worry, awareness, or mindfulness experience, and thus was not correlated with any of these individual differences measures. However, the ERN and Pe were related to these trait variables, possibly because these variables reflect aspects of error detection, a process which has been linked to the ERN and Pe in previous studies. Therefore, based on our findings, it is difficult to determine whether the mindfulness induction was an effective manipulation of mindfulness since the ERAS was the only neural correlate affected by the manipulation. One possible explanation is that the mindfulness induction induced a state of greater relaxation rather than a state of greater mindful awareness.

Although the present study found mixed results with respect to the effectiveness of the mindfulness induction on error processing, various studies have documented the beneficial

effects of mindfulness meditation on many aspects of physical and mental health, including stress reduction, improved cognitive control, and enhanced emotion regulation. While interest in the neuropsychological effects of mindfulness is a relatively new field of interest, there is emerging evidence that mindfulness meditation may cause neural changes that result in enhanced regulation of attention, emotion, and other aspects of executive control. Thus, future research should be dedicated to examining the effects of mindfulness on the many aspects of executive control. In particular, understanding how mindfulness affects the brain's response to negative life events, such as mistakes and errors, could play an important role in the development and improvement of treatment for various clinical disorders, as well as the cultivation of healthy mental and physical health.

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Tables and Figures

**Table 1.** Mean Pe amplitude (in  $\mu\text{V}$ ) as a function of site separated by correct and error trials

Site	Correct	Error	Average
Cz	.84	4.53	2.69
FCz	.84	5.64	3.24
Fz	.85	4.91	2.88
Pz	2.37	4.89	3.63

**Table 2.** Log alpha power values as a function of condition separated by correct and error trials

Condition	Correct	Error
Mindfulness	1.53	1.45
Control	1.40	1.39

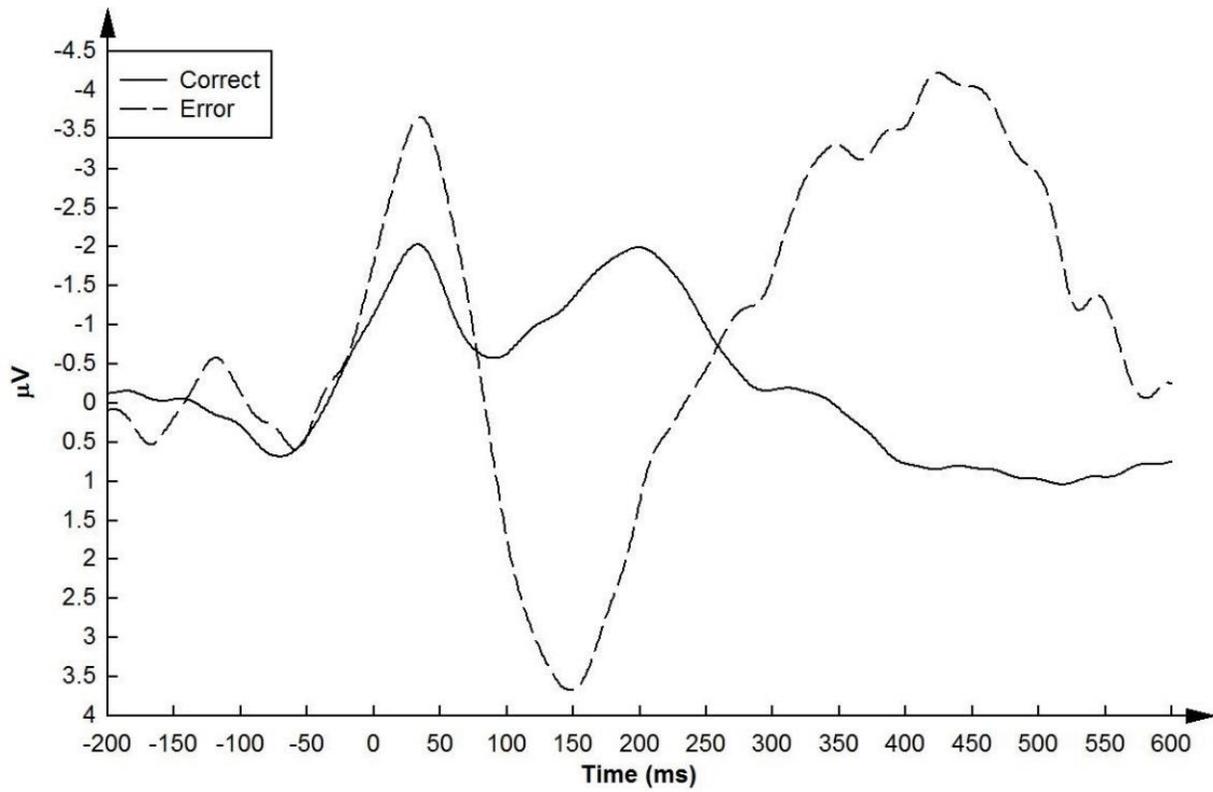
**Table 3.** Log alpha power values as a function of epoch separated by correct and error trials

Epoch	Correct	Error	Average
0	1.36	1.46	1.41
256	1.46	1.35	1.40
572	1.50	1.34	1.45
768	1.52	1.44	1.48
1024	1.49	1.45	1.47

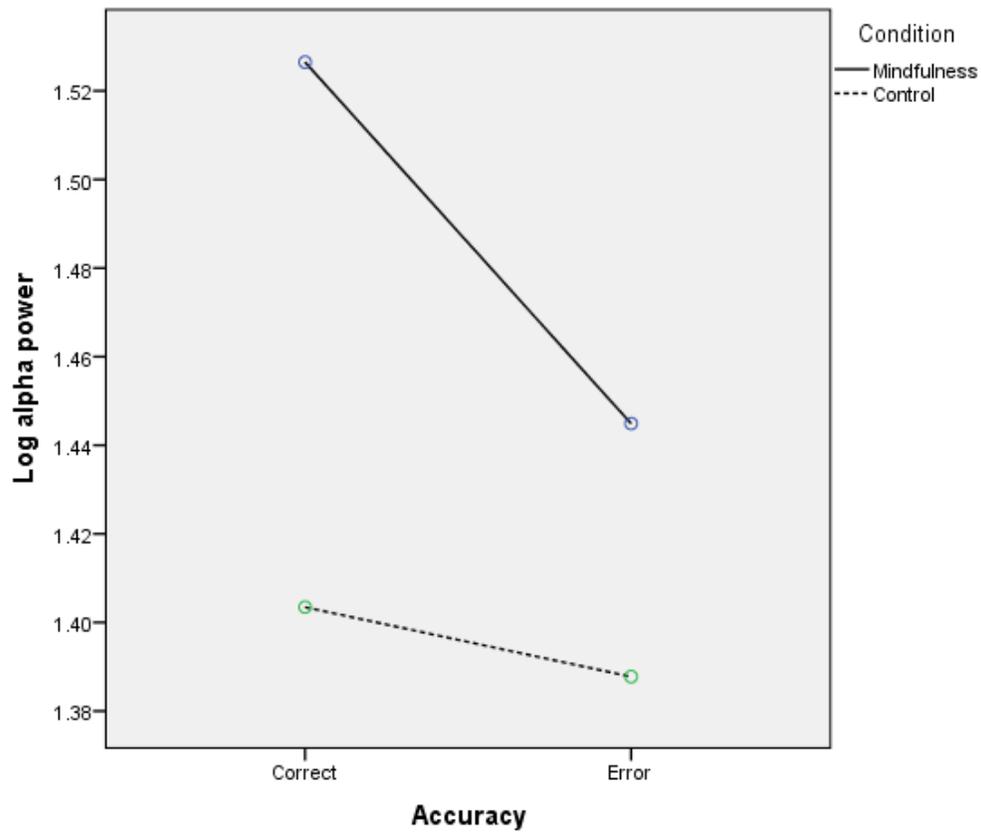
**Table 4.** Log alpha power values as a function of site separated by correct and error trials

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

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**Figure 1.** Response-locked grand-average waveforms for correct and error trials. Time 0 is the time of the button press.



**Figure 2.** Log alpha power separately for correct and error trials for mindfulness and control conditions.