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Attention-Mediated Neural and Behavioral Oscillation and Their Relationship to Dispositional Mindfulness

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by

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ABSTRACT

Over the past decades, there has been growing interest in mindfulness-based interventions (MBIs) and their association with attention. Preliminary research suggests that self-regulation of attention may mediate clinical benefits of MBIs. Although daily practice of mindfulness exercise and participation in MBI can produce noticeable intra-personal improvement in mindfulness skills over time, it is of greater theoretical significance to assess inter-individual differences in mindfulness and demonstrate the degree to which various levels of dispositional mindfulness relate to outcomes of interest. Furthermore, there are recent developments focusing on systematic temporal fluctuations in the brain waves and subsequent behavioral performance, which has been proposed as an underlying mechanism of attention. Thus, the current study aimed at evaluating the temporal pattern of behavioral performance and concurrent EEG data in visual cueing tasks via time-frequency techniques and investigating whether behavioral and neural parameters of selective attention in visual cueing tasks are associated with levels of dispositional mindfulness.

To address these research questions, three experiments were conducted wherein participants completed an endogenous cueing task (n = 44, Experiment 1), an exogenous cueing task (n = 42, Experiment 2), or an endogenous cueing task with concurrent EEG recordings (n = 27). Additionally, participants from Experiment 1 and Experiment 2 completed self-report questionnaires including Mindfulness Attention Awareness Scale (MAAS), Five Facets Mindfulness Questionnaire (FFMQ), and Adult ADHD Self-Report Scale (ASRS). The results from the endogenous attention task suggest significant oscillatory activities at Delta, Theta, and Beta frequency bands for discrimination accuracy and at Delta, Alpha, and Beta frequency bands for reaction time. Likewise, behavioral data from the exogenous attention task indicates significant increases in evoked Theta and Alpha power in discrimination accuracy and reaction time, respectively. EEG data also support significant power spectral suppression in frontocentral electrodes in Delta and Theta bands when participants' covert attention shifted either to the left or right target location compared with no-target condition. Moreover, we observed a positive correlation between FFMQ subscale scores and evoked power suggesting that levels of dispositional mindfulness are associated with spatial visual attention. Clinical implications and limitations of the current study will be further discussed.

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CHAPTER 1

INTRODUCTION

Over the past decades there has been growing interest in mindfulness-based interventions (MBIs) and their association with attention (Bergomi, Tschacher, & Kupper, 2013a; van der Velden et al., 2015). A large body of research demonstrated that MBIs have shown effectiveness at reducing various physical and psychological problems (Kabat-Zinn, 2003; Keng, Smoski, & Robins, 2011; Khoury et al., 2013; van der Velden et al., 2015). Such popularity and mounting clinical evidence of MBIs has shifted research focus to the underlying mechanisms that contribute to clinical outcomes. Various mechanisms of change have been proposed including emotion regulation, reduced cognitive reactivity and rumination, meta awareness (i.e., “reperceiving” or decentering), and self-compassion (Chiesa, Anselmi, & Serretti, 2014; Coffey & Hartman, 2008; Gratz & Tull, 2010).

Among these proposed mechanisms, the current study investigates self-regulation of attention. Mindfulness exercise often involves attention as people are asked to focus their attention on bodily sensations associated with breathing (e.g., breathing meditation) and direct their attention to different parts of their body (e.g., body scan), and there is evidence that continued practice of mindfulness enhances attentional control. (Bergomi et al., 2013a; Bishop et al., 2004). Furthermore, mindfulness training improves the ability to maintain and shift the focus of attention with full awareness of one’s goals, and this in turn reduce vulnerability to elaborative and negative thinking patterns and promote emotion regulation (Shapiro, Carlson, Astin, & Freedman, 2006). While MBIs conceptualize mindfulness as a trainable skill, dispositional mindfulness that is relatively stable over time but is sensitive to changes following MBIs also warrants further research attention because dispositional mindfulness may be different from a transient mindfulness state induced by MBIs (Davidson, 2010). However, empirical studies are lacking in the literature that investigate the relationship between individual trait differences in dispositional mindfulness and both sustained and selective attention via multiple assessment methods.

In order to address this question, we build on a line of research that examines temporal fluctuations of behavioral performance and neuronal activity in selective attention tasks (Bonnefond, Kastner, & Jensen, 2017; Busch & VanRullen, 2010; Song, Meng, Chen, Zhou, & Luo, 2014). Previous research on the neurophysiological mechanism of visual attention revealed that ongoing rhythmic waves in the human brain are modulated by attention (i.e., shifting attention toward vs away from the visual target stimuli) (Salmelin, Hari, Lounasmaa, & Sams, 1994; VanRullen, 2013). Furthermore, such attention-mediated neural oscillations are associated with excitability of neurons that are responsible for processing attended stimuli as well as perception and behavioral performance in cognitive tasks (Rau, Plewnia, Hummel, & Gerloff, 2003; L. Wang, Saalmann, Pinsk, Arcaro, & Kastner, 2012; Zarkowski, Shin, Dang, Russo, & Avery, 2006). Although recent magnetoencephalography (MEG) and electroencephalography (EEG) studies demonstrated that sustained attention toward a potential location of the visual target modulates neural oscillations in various frequency bands (e.g., alpha and gamma), research effort is needed to examine the presence of ensuing rhythmic activity in behavioral performance.

The current study addresses the following research questions: (1) whether behavioral performance in visual cueing tasks manifests rhythmic oscillatory patterns, (2) whether behavioral and neural parameters of selective attention in visual cueing tasks are associated with levels of dispositional mindfulness, and (3) whether EEG activity during visual cueing tasks shows systematic fluctuations over time. To address these questions, our novel cueing paradigm systematically varies the cue-to-target intervals in an increment of 24 ms, and this procedure will allow us to capture the moment-by-moment changes in behavioral and neuronal parameters. In particular, it is the first study to examine the association between oscillatory activity in behavioral and neuronal data and dispositional mindfulness. The subsequent sections present a review of previous mindfulness research including clinical applications of MBIs and the relationship between dispositional mindfulness and attention, and provide a neuroscience account of spatial attention focusing on oscillatory activity in neural and behavioral data (Chapter 2), discuss problems of extant research, significance of the present study, and hypotheses (Chapter 3), describe methods and report findings from three experiments (Chapter 4 through 7), and finally discuss interpretations and implications of the findings and recommendations for future direction (Chapter 8).

CHAPTER 2

REVIEW OF THE LITERATURE

2.1. Mindfulness and Mental Health

2.1.1. Growing Interest in Mindfulness

Over the past decades, there has been a growing interest in mindfulness (Bishop et al., 2004). Since the Mindfulness Based Stress Reduction (MBSR; Kabat-Zinn, 1982) was first introduced as a treatment of chronic pain in the late 1970's, a number of mindfulness-based interventions (MBIs) have been developed to target psychological problems such as recurrent major depressive disorder (Mindfulness Based Cognitive Therapy (MBCT); Segal, Williams, & Teasdale, 2002), anxiety disorders (Acceptance and Commitment Therapy (ACT); Hayes, Strosahl, & Wilson, 1999), and borderline personality disorder (Dialectical Behavior Therapy (DBT); Linehan, 1993). Nowadays, a greater number of individuals in general population seek mindfulness training as a means to promote wellbeing and manage stress. For example, the National Health Interview Survey (Kachan D et al., 2017) demonstrates that 12-month engagement rates in the US workforce increased from 8.0% in 2002 to 9.9% in 2007 for mindfulness practices.

Several factors contributed to the rapid growth of MBIs as well as personal mindfulness practices. First, some MBIs were developed to address physical and psychological conditions on which pre-existing treatments have limited therapeutic effects. The original 8-week MBSR program aimed to improve pain intensity and functional limitations in chronic pain patients who did not respond to traditional pharmacological treatment (Kabat-Zinn, 1994). Likewise, borderline personal disorder was once considered untreatable among therapists (Silk, 2008). Since the inception of DBT, however, such consensus in the field has changed, and a recent meta-analysis on sixteen treatment outcome studies demonstrated a moderate effect size of DBT on suicidal and self-injurious behaviors with low drop-out rates (27.3%) (Kliem, Kröger, & Kosfelder, 2010).

Second, the accumulation of strong clinical evidence for MBIs drew further research attention to mindfulness. A recent meta-analysis on MBIs reports that their overall effect sizes were estimated to be moderate for physical (e.g., chronic pain) and psychological conditions (e.g., depression), and their mean effect sizes were even comparable to those for conventional psychotherapy and pharmacological treatments (Khoury et al., 2013). Furthermore, the growing empirical evidence of MBIs stimulated systematic attempts to expand their clinical application to a broader range of psychological and physical conditions. For example, the current literature documents that MBSR has been applied to a variety of physical and psychological conditions with demonstrated efficacy, such as generalized anxiety disorder (Hoge et al., 2015), depression (Marchand, 2012), social phobia (Goldin & Gross, 2010), cancer (Cramer, Lauche, Paul, & Dobos, 2012), and sleep disturbance (Winbush, Gross, & Kreitzer, 2007) as well as chronic pain (Rosenzweig et al., 2010).

Third, increased public awareness and the development of online and offline mindfulness programs contributed to an increase in the number of mindfulness practitioners. Many health care providers acknowledge and recommend mindfulness practice as a useful approach to stress management and improvement of quality of life (Kachan D et al., 2017). In addition, the popularity of mindfulness approaches in the health care system allowed laypeople to identify mindfulness training as health-promoting techniques rather than religious practice, and this change in public perception lowered the barrier to mindfulness practice (Kachan D et al., 2017). Furthermore, due to the development of mobile phone applications, Internet-based meditation programs, and social media groups, mindfulness programs became more affordable and easily accessible (Spijkerman, Pots, & Bohlmeijer, 2016).

To sum, research on MBIs has grown its popularity and influence on the health care system and general population. Solid clinical evidence and increased public awareness of far-reaching benefits of MBIs changed the topography of mental health research. Despite its rapid growth, our understanding of mindfulness is still in an infant stage where methodological and theoretical challenges are yet to be resolved. For example, a consensus has not been reached with regard to the operational definition of mindfulness, and underlying mechanisms of MBIs remain unclear (W. Brown & R. Ryan, 2003). To increase our understanding of mindfulness and advance current MBIs, further research attention is warranted.

2.1.2. Definition and Key Components of Dispositional Mindfulness

Mindfulness has long been practiced in Eastern meditation traditions and has its theoretical and methodological roots in Buddhism. In the Pali term, mindfulness means to ‘remember’ or ‘to be aware’ (Thera, 2014). Although such working definition may suffice to communicate its meaning among practitioners, few scientific approaches to mindfulness have been undertaken in the East, including operationally defining mindfulness. This is largely due to the consensus among Buddhist teachers and scholars that mindfulness is a process that can be observed through direct experience, but not through any analytical approaches (Thera, 2014). In the West, on the other hand, its increasing popularity and clinical benefits facilitated systematic attempts to conceptualize mindfulness using Western scientific methods such as self-report questionnaires, behavioral tasks, and psychophysiological assessments.

Before further review of western conceptualizations of mindfulness, it is noteworthy that the term “mindfulness” is used in different ways (Davidson, 2010). On one hand, mindfulness is operationalized as a personal trait that is stable over time, but sensitive to changes by various factors including developmental history and mindfulness training. Dispositional mindfulness is often assessed by self-report questionnaires, and efforts have been made recently to identify physiological and neural correlates (Creswell, Way, Eisenberger, & Lieberman, 2007; Laurent, Laurent, Nelson, Wright, & Sanchez, 2015). On the other hand, mindfulness is assessed during or shortly after an informal mindfulness exercise or a formal treatment program such as MBSR and MBCT. In this case, mindfulness is viewed as a transient state, and state mindfulness and its effects are often captured by concurrent changes in theoretically relevant variables such as emotional and thought processes, cognitive functions, as well as biological markers. Although dispositional mindfulness is considered malleable to psychological interventions and continued informal training (Davidson, 2010), how much mindfulness training is needed for a significantly measurable change in dispositional mindfulness (dosage effect) remains unclear.

A number of dispositional mindfulness definitions have been proposed in the literature. For instance, Kabat-Zinn defined mindfulness as, “paying attention in a particular way: on purpose, in the present moment, non-judgmentally” (Kabat-Zinn, 1994, p. 4). His definition highlights the importance of paying attention to the present-moment experience (e.g., bodily sensations, thought, images, and memories) without judging and negatively responding to it. Likewise, Bishop and colleagues (2004) underscored self-regulation of attention as a primary aspect of mindfulness while acknowledging attitudinal components of curiosity and acceptance. These authors argued that paying attention to the present-moment experience requires individuals to stay open (curiosity) and to accept one's experience without attempting to suppress or avoid it (acceptance). Other components of dispositional mindfulness have been suggested in the literature: a decentered perspective that is devoid of self-focus or self-absorption (Lau et al., 2006), non-reactivity or non-habitual responding to one's experience and the ability to describe experience in words (Baer, Smith, Hopkins, Krietemeyer, & Toney, 2006), non-identification with one's own experiences, and insightful understanding (Bergomi, Tschacher, & Kupper, 2013b).

2.1.3. Salutary Effects of Mindfulness Practice

A large body of research suggests that MBIs produce far-reaching impacts on physical and psychological conditions as well as human functioning in major life domains. These salutary effects have been demonstrated for various age groups (Biegel, Brown, Shapiro, & Schubert, 2009; Creswell et al., 2012; Regehr, Glancy, & Pitts, 2013), for both clinical and non-clinical populations (Khoury et al., 2013), and in individual and group psychotherapy (Visted, Vøllestad, Nielsen, & Nielsen, 2015). Current literature documents that MBIs are beneficial for individuals with medical problems such as chronic pain (Chiesa & Serretti, 2011), terminal illness such as cancer and HIV (Carlson, Speca, Patel, & Goodey, 2003; Creswell, Myers, Cole, & Irwin, 2009), sleep disturbance and sleep-interfering behavior such as rumination (Winbush et al., 2007), and multiple sclerosis (R. Simpson et al., 2014).

MBIs have been also shown to provide clinically meaningful improvements in symptoms of psychological disorders (see Khoury et al., 2013 for review and meta analysis). The meta-analysis results show that effect sizes were medium to large (Hedge's *g* = .53-1.00) for MBIs targeting anxiety disorders and depression (Khoury et al., 2013). In addition, there is empirical evidence that MBIs are effective in the treatment of eating disorders such as anorexia nervosa and binge eating disorder (Wanden-Berghe, Sanz-Valero, & Wanden-Berghe, 2010), Post-Traumatic Stress Disorder (PTSD; Banks, Newman, & Saleem, 2015), and ADHD (Van de Weijer-Bergsma, Formsma, de Bruin, & Bögels, 2012). Recently, some attempts have been made to apply mindfulness training in the treatment of persistent and severe mental illness such as Schizophrenia and bipolar disorder either as a stand-alone program or as a core component (see Davis & Kurzban, 2012 for review). The authors concluded that although many studies lack methodological rigor with reduced internal validity, preliminary evidence is promising such that MBIs may reduce distress associated with their psychiatric illness and the frequency of psychiatric hospitalization while improving coping skills (Davis & Kurzban, 2012).

Apart from clinical benefits, mindfulness improves functioning in major life domains and reduce distress associated with a daily routine. Empirical studies demonstrated that MBIs reduce work-related stress and burn-out (Pipe et al., 2009; Poulin, Mackenzie, Soloway, & Karayolas, 2008). There is also evidence that dispositional mindfulness is positively correlated with job performance, but negatively with turnover intention (Dane & Brummel, 2014). Interpersonally, dispositional mindfulness was positively associated with key factors of relationship quality, including relationship satisfaction, the ability to effectively communicate one's needs and resolve interpersonal conflicts, and empathy (Barnes, Brown, Krusemark, Campbell, & Rogge, 2007; Wachs & Cordova, 2007). Furthermore, individuals with high trait dispositional mindfulness were found to experience reduced emotional distress and less frequently express negative emotions (e.g., anger) toward other people when managing interpersonal conflicts (Barnes et al., 2007). Furthermore, MBIs have positive influence on personal and subjective domains of life such as psychological wellbeing (K. W. Brown & R. M. Ryan, 2003; Grossman, Tiefenthaler-Gilmer, Raysz, & Kesper, 2007), quality of life (Carlson et al., 2003), spirituality (Carmody, Reed, Kristeller, & Merriam, 2008).

To sum up, various mindfulness-based approaches have been developed with increased recognition by healthcare professionals as well as ordinary people. Long-lasting Eastern meditation practice was successfully adopted to Western society as a vehicle to promote a wide range of physical and psychological conditions, and empirical research provides evidence for the efficacy of MBIs. Despite the growing popularity and research interest, mechanisms of action remain unclear. Since self-regulation of attention is generally considered a core process of dispositional mindfulness (2004), one promising avenue for exploring beneficial effects of MBI is to delineate the relationship between attention and psychological problems and evaluate whether mindfulness training mediates such relationship.

2.2. Attention and Mental Health

2.2.1. Impaired Attention in Mental Disorders

Recently, research efforts have been made to identify transdiagnostic processes that develop and maintain symptoms across disorders (Ellard, Fairholme, Boisseau, Farchione, & Barlow, 2010; Field & Cartwright–Hatton, 2008; Gruber, Eidelman, & Harvey, 2008; Nolen-Hoeksema & Watkins, 2011). Epidemiological studies report that high comorbidity among mental disorders is the rule rather than the exception (Kessler, Chiu, Demler, & Walters, 2005; Kessler & Merikangas, 2004). In addition, proposed transdiagnostic mechanisms (e.g., emotion regulation and experiential avoidance) were found to correlate with a broad range of psychological problems such as anxiety disorders, major depression, eating disorder, and substance abuse, indicating that these latent variables may underlie psychopathology (Aldao, Nolen-Hoeksema, & Schweizer, 2010; Hayes, Luoma, Bond, Masuda, & Lillis, 2006). Furthermore, psychological interventions that target transdiagnostic processes result in meaningful improvements in symptomatology of anxiety and depression, and negative mood (Ellard et al., 2010; Farchione et al., 2012). These combined results provide support that transdiagnostic mechanisms may exist and causally relate to various types of psychopathology. The identification of these transdiagnostic mechanisms can increase our understanding of how various psychological problems develop and are maintained, and thus this knowledge is applied to enhance efficacy and efficiency of the current psychological interventions.

Among proposed transdiagnostic mechanisms, impairment in attentional processing is gaining more research ground. A large body of literature documents that attention bias, defined as increased perceptual sensitivity in favor of threat-related stimuli, is common across various anxiety disorders including generalized anxiety disorder (GAD), social phobia, specific phobias (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & Van Ijzendoorn, 2007; Weierich, Treat, & Hollingworth, 2008). For example, a recent meta-analysis of experimental studies using dot-probe and emotional Stroop paradigms demonstrated that anxious individuals showed significant within-group effects of the threat-related bias while non-anxious controls did not show such within-group difference (see Bar-Haim et al., 2007 for review). One may argue that such attention bias allows anxious individuals to detect threat more quickly and thus mitigate the potentially negative situation. Although between-subjects effects of attention bias were significantly greater for anxious participants than for control participants, the effect sizes of within- and between-group effects were comparable, indicating that the group difference in the threat-related bias is largely due to significant attention bias in anxious individuals (Bar-Haim et al., 2007). Furthermore, attention bias toward threat-related information was present only when a threat or emotion cue was followed closely in time (less than 100 ms) by a target (Derryberry & Reed, 1994). These results suggest that anxious individuals rather have difficulty in disengaging attention from threat-related stimuli, which disrupts the processing of information followed by emotional stimuli (Bar-Haim et al., 2007; Fox, Russo, & Dutton, 2002).

While anxiety disorders are largely associated with attention bias toward threat information, individuals with mood disorders show a different profile of attention problems. For example, depressed individuals were found to have a tendency to selectively attend to negative information, and to ruminate on feelings of inadequacy and worthlessness, which may further distract their attention away from on-going tasks (MacLeod, Mathews, & Tata, 1986; Nolen-Hoeksema & Watkins, 2011). Based on studies using a dot-probe task or an eye-tracking device, depressed participants were found to preferentially attend to sad faces while the control participants avoided sad faces in favor of happy faces (Caseras, Garner, Bradley, & Mogg, 2007; Joormann & Gotlib, 2007). Furthermore, Beevers and Carver (2003) demonstrated that attention bias together with life stress predicted increased dysphoria at 7-week follow-up, indicating that attention bias toward negative information prolongs the negative mood state and contributes to the maintenance of depressive symptoms (Baert, De Raedt, Schacht, & Koster, 2010).

In addition to impairment in selective attention, there is evidence that people with mood disorders are impaired on sustained attention. For instance, euthymic patients with Bipolar I disorder were evaluated on the Rapid Visual Information Processing (RVIP), which requires the detection of pre-determined three-digit sequence targets, and Bipolar I Disorder patients showed lower target detection rates and longer response latency compared to control participants (Clark, Iversen, & Goodwin, 2002). Likewise, Maalouf et al. (2010) evaluated performance in the Rapid Serial Visual Presentation (RSVP) task which requires participants to continuously monitor a rapidly displayed stream of stimuli and identify target(s). The authors found lower detection rates in the Bipolar Disorder group compared to control, indicating deficits in sustained attention. The authors argue that the bipolar-specific deficit in sustained attention is linked to emotional lability and high impulsivity, which are not as much salient in depression patients (Maalouf et al., 2010).

Furthermore, impairments in executive function are associated with mood disorder (Fossati, Ergis, & Allilaire, 2002; Paelecke-Habermann, Pohl, & Leplow, 2005). According to the Attention Network Model (Posner & Rothbart, 2007), executive attention mainly concerns conflict and error monitoring and response inhibition. This cognitive capacity involves evaluating information with respect to expectations and current goals, which promotes flexible adaptation to the environment and goal attainment. Neuropsychological accounts of mood disorder suggest that persistent mood disturbances are due to abnormal inputs of the amygdala to anterior cingulate cortex and prefrontal cortex, which are indicated for executive functions, particularly conflict monitoring and inhibitory control (Paelecke-Habermann et al., 2005; Strakowski, Adler, & DelBello, 2002). Consistent with this view, Paelecke-Habermann et al. (2005) administered a Stroop task wherein participants were asked to name the color of the word (e.g., the word RED presented in green) while suppressing word information. The authors found that compared to control participants, patients with major depressive disorder (MDD) showed longer response latency, suggesting difficulty monitoring goal-relevant information (i.e., the color of the word) and inhibiting a response that interferes with task performance (e.g., semantic processing of the word). Such cognitive impairments may reflect the inability of those with mood disorder to disengage from perseverative thought processes such as rumination on the negative mood state (Lo & Liu, 2017).

Literature also suggests significant impairments in various types of attention in individuals with severe mental illness (SMI) such as schizophrenia. First, impaired sustained attention has been documented in high-risk groups for Schizophrenia (e.g., first-degree relatives of patients with Schizophrenia) as well as individuals with Schizophrenia (Chen & Faraone, 2000; Chen et al., 1998; Nuechterlein et al., 1990). For example, Demeter, Guthrie, Taylor, Sarter, and Lustig (2013) reported that compared to healthy control, patients with Schizophrenia showed reduced overall performance in the Sustained Attention Task (SAT) with higher vulnerability to distraction. Likewise, when patients with Schizophrenia were compared to healthy control subjects, patients with

Schizophrenia showed impaired sensitivity and thus reduced sustained attention, as measured by the Degraded Symbol Continuous Performance Test (DS-CPT) (Kumar et al., 2010). These results are consistent with functional imaging studies demonstrating reduced activation when individuals with schizophrenia engage in visual information processing (Gur et al., 2007; Martínez et al., 2008). However, effect sizes were found to be small to medium, and thus it remains unclear whether sustained attention deficits are etiologically independent of symptoms of schizophrenia.

Second, evidence for selective attention deficits are mixed in SMI population. Breton et al. (2011) administered the Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002) and found no group difference in orienting (ANTo) between patients with Schizophrenia and control subjects. In other words, the ability to shift attention to the cued location by using the spatial cue is comparable between the groups. Similarly, Tregellas, Smucny, Eichman, and Rojas (2012) conducted an fMRI study by presenting oddball stimuli to one ear and either silence or a distracting white noise stimulus to the other ear, and found that both healthy subjects and individuals with Schizophrenia performed with similar accuracy rates under the silent condition. However, accuracy rates were lower for the patient group when the oddball stimulus was concurrently presented with a distracting noise (Tregellas et al., 2012). These tasks test the ability to orient attention to spatial or auditory location, and discriminate target from distractor stimuli. It is possible that performance is moderated by task difficulty or presence of competing stimuli. Although patients' performance is on par with healthy controls when a task is relatively simple or does not involve other distracting stimuli. However, individuals with schizophrenia may find it harder to perform these tasks.

Consistent with behavioral results, fMRI data support the group difference that a distributed network of brain regions associated with selective attention were more active under the distraction condition for patients with Schizophrenia than for healthy controls, which indicates that patients with Schizophrenia need to recruit more attentional resources when a distracting stimulus is present (Tregellas et al., 2012). These results suggest that cognitive impairment in selective attention and increased distractibility may disrupt information processing in schizophrenia, which in turn contributes to incoherent thinking and disorganized behavior.

Third, there is strong evidence for deficits in executive attention in people with Schizophrenia. Using the Attention Network Test (Fan et al., 2002), Breton et al. (2011) demonstrated that compared to control subjects, patients with Schizophrenia showed greater conflict effect (ANTc), which was calculated by subtracting the mean reaction time of congruent flanker conditions (i.e., flankers point in the same direction as the target arrow) from that of incongruent flanker conditions (i.e., flankers and the target arrow point in opposite directions). In other words, the longer reaction time in incongruent flanker conditions indicates that patients experienced greater difficulty resolving conflicting information. A recent meta-analysis of forty-one neuroimaging studies supports evidence for altered activity in brain regions such as dorsolateral prefrontal cortex (DL-PFC), anterior cingulate cortex (ACC), and mediodorsal nucleus of the thalamus, and hyperactivation in these brain regions may underlie disrupted top-down cognitive control (Minzenberg, Laird, Thelen, Carter, & Glahn, 2009). Breton et al. (2011) argued that disorganized speech and behavior are attributed to impaired executive attention in schizophrenia. Furthermore, poor executive attention negatively affects behavioral and emotional regulatory functions involving planning according to internal goals and environmental constraints, inhibiting irrelevant cognitive processes for optimal use of cognitive resources, and ability to regulate emotion (Orellana & Slachevsky, 2013).

In sum, a large body of evidence suggests that problems with attentional control are present across a wide range of mental disorders. However, it remains unclear whether the co-occurring attention problems etiologically contribute to symptom development and its maintenance or attention deficit is a mere epiphenomenon or result of disorder-specific symptoms. Thus, further longitudinal and experimental studies are warranted to investigate the causal relationship between attention deficit and symptom severity of various mental disorders.

2.2.2. Attention-focused Treatment of Psychological Disorders

The studies mentioned above provide support that attention problems may contribute to the development or maintenance of various psychological disorders. However, more convincing evidence will be drawn from experiments that directly manipulate attentional processing and examine their effects on symptom severity. Thus, this section will introduce five attention-focused training programs that target psychopathology: Attention Training Technique (ATT; Wells, 2002), Cognitive Control Training (CCT; Siegle, Ghinassi, & Thase, 2007), Task Concentration Training (TCT; Bögels, 2006), Cognitive Bias Modification (CBM), and cognitive remediation (CR) programs.

Based on her self-regulatory executive function (S-REF) model, Wells (2002) proposed that a problematic pattern of cognition and metacognition such as rumination, worry, attention bias toward threat, and excessive self-focused attention is responsible for psychological disorders, and suggests that the key to treatment is to promote flexible attentional control. Concurrently, Wells (2002) developed the Attention Training Technique (ATT) where patients with an emotional disorder complete auditory attention exercises involving selective attention, attention switching, and divided attention. For example, participants listen to competing sounds (e.g., sounds of a bell, footsteps, and wind through trees) and as guided by the instructor, switch to one sound while tuning out all other sounds in the background. ATT has been applied to a wide range of psychological disorders, and clinical studies indicate improvements in attentional control as well as symptoms of panic disorder (Wells, 1990), major depression (Papageorgiou & Wells, 2000), hypochondriasis (Papageorgiou & Wells, 1998), auditory hallucinations in schizophrenia (Wells, 2007), and PTSD (Callinan, Johnson, & Wells, 2015). However, these results must be interpreted with caution because most of the studies either lacked a control condition or used a small sample, which warrants further replication in a larger randomized-controlled study. Moreover, practice effects need to be isolated by selecting separate attention measures that assess changes in the corresponding attention types, and further evidence is needed to evaluate the degree to which the effects of ATT are transferred to other domains of cognitive and emotional processes.

Second, Cognitive Control Training (CCT; Siegle et al., 2007) is methodologically similar to ATT but is driven by neurobiological research demonstrating that increased and sustained amygdala reactivity to emotional stimuli and decreased prefrontal inhibitory function are common in major depression (Drevets & Raichle, 1998). Neurobiological assessment indicates decreased dorsolateral prefrontal cortex

(DL-PFC) reactivity to negative words and increased PFC activity for the hardiest stimuli condition (5 digits) on the digit sorting task (Gronwall, 1977). These results suggest that reduced top-down control may etiologically contribute to the development or maintenance of depression as individuals become more vulnerable to emotional disturbances and egodystonic perseverative thought processes such as rumination (Siegle & Hasselmo, 2002). Thus, CTT posits that repeated engagement in tasks activate PFC-mediated executive attention, and as a result strengthen inhibitory control with improvements in depressive symptoms (Siegle et al., 2007). In order to increase inhibitory prefrontal control, CTT uses two cognitive tasks: Wells (2002)’s ATT and a variation of Paced Auditory Serial Attention Task (Gronwall, 1977), in which a series of single digits are presented and participants are asked to sum up each new digit and the one that is immediately followed. Depressed participants who received CCT plus treatment as usual (TAU) showed greater improvements in self-reported depressive symptomatology and rumination than those in the TAU only condition (Siegle et al., 2007). Although further research is needed to evaluate CTT as a stand-alone neuropsychological intervention, CTT appears to mediate symptoms of depression via proposed mechanisms and shows its clinical potential for treatment of depression.

Third, Task Concentration Training (TCT; Bögels, Mulkens, & De Jong, 1997) was designed to treat symptoms of social phobia. Drawn from the observation that people with social phobia excessively focus on their bodily symptoms (e.g., blushing, trembling, and sweating) and negative cognitions about experiencing these symptoms, TCT participants are gradually exposed to fear-provoking social situations and learn to redirect their attention to the social tasks. For example, participants are asked to stroll in a crowded park while keeping his task-specific goal (e.g., planning where to go next) in mind and continuously monitoring his or her surroundings. A number of studies demonstrated that TCT is effective in reducing symptoms of social phobia and self-focused attention (Bögels, 2006; Bögels et al., 1997). Bögels (2006) argues that dysregulation of selective attention manifests in the form of fixation on physiological reactions to a social task, which serves to develop heightened sensitivity to physiological reactions and maladaptive beliefs about them. By learning to shift the focus from interoceptive to externa and task-relevant information, individuals with social phobia are expected to experience a reduction in physiological symptoms through decreased self-focused attention (Bögels, 2006). However, it is not clear whether TCT is generalizable to treat other psychological conditions, and whether the efficacy of TCT was superior to applied relaxation across the majority of assessment measures (Bögels, 2006).

Fourth, Cognitive Bias Modification (CBM) programs were designed to address the tendency to preferentially attend to negatively valenced information (attention bias) or interpret ambiguous information in a negative way (interpretation bias). While the pervious interventions predominantly focused on attention bias in relation to anxiety disorders, ABMs demonstrated broader application potential as a treatment of depression as well as anxiety disorders (Browning, Holmes, Charles, Cowen, & Harmer, 2012; Yang, Ding, Dai, Peng, & Zhang, 2015). In a typical CBM program, a dot probe paradigm is used with a varying contingency of a probe following either neutral or negative emotional stimuli (MacLeod, Campbell, Rutherford, & Wilson, 2004). For example, the percentage at which the probe replaces neutral stimuli increases to 80 percent for those who show attention bias toward threatening stimuli, and such manipulation is necessary to assist participants in developing a stronger implicit association between neutral stimuli and the target probe, thus reducing attention bias (MacLeod et al., 2004). Another type of a common CBM program presents a sentence with a fragmented word (“b_r_ng”) that participants must solve or an ambiguous sentence (“They discussed the priest’s convictions”) that participants select either a threatening or neutral interpretation (Hallion & Ruscio, 2011).

One meta-analysis estimated that the effect size of CBM be large (d = 1.16) on attention bias and medium (d = 0.61) on anxiety symptoms (Hakamata et al., 2010). Similarly, another meta-analysis completed by Hallion and Ruscio (2011) reports that the effect size of CBM is medium on cognitive bias (g = 0.49) and small on anxiety symptoms (g = 0.13). However, the authors note that the effect size of CBM on depressive symptoms was small and non-significant after accounting for publication bias (Hallion & Ruscio, 2011). Hallion and Ruscio (2011) also highlight that effect sizes of CBM were larger when clinical samples versus healthy individuals were tested, and when a concurrent stressor existed at the time of CBM administration, indicative of interaction of the effects of CBM with a stressor. Overall, these results suggest that CBM produces reliable improvements in cognitive bias and symptom severity. However, further research is needed to explicate the relative contribution of CBM to the relationship between cognitive bias and changes in symptomatology and to identify moderators that account for the variability of effect sizes across CBM programs.

Finally, cognitive remediation (CR) has been applied to mainly severe mental illness such as schizophrenia and bipolar disorder but also other mental disorders including depression and anorexia nervosa (Bowie et al., 2013; Demant, Almer, Vinberg, Kessing, & Miskowiak, 2013; McGurk, Twamley, Sitzer, McHugo, & Mueser, 2007). Cognitive impairment is a core feature of severe mental illness, and is known to have negative impacts on functioning in major domains such as work, home, and social relationships (McGurk & Mueser, 2004; Mueser, 2000). Since cognitive functioning is a strong predictor of response to psychiatric rehabilitation, CR programs have been developed to improve various cognitive functions including but not limited to attention/vigilance, speed of processing, verbal and non-verbal working memory, verbal and visual learning and memory, reasoning and problem solving, and social cognition (McGurk et al., 2007). However, there are significant differences among CR programs in terms of targeted cognitive functions, delivery method (e.g., paper and pencil tasks vs computer-based exercises), and treatment modality (e.g., individual vs group) (Medalia & Choi, 2009).

There is evidence that CR produce mild to moderate improvements in cognitive performance, and both functional and symptom outcomes (Demant et al., 2013; McGurk et al., 2007; Medalia & Choi, 2009; Tchanturia, Lounes, & Holttum, 2014). A meta-analysis of CR in schizophrenia reported medium effect sizes for cognitive performance in six cognitive domains (0.39-0.54), small overall effect size for symptomatology (0.28), and moderate overall effect size for psychological functioning (0.35) (McGurk et al., 2007). In a randomized controlled study on patients with bipolar disorder, Demant et al. (2013) found that a 12-week CR program was effective in improving verbal memory, sustained and divided attention, executive function, and psychosocial function as well as subjective cognitive difficulties and depressive symptoms. As CR is gaining further clinical evidence, attempts have been made to apply CR to other mental disorders. For example, Bowie et al. (2013) reported that treatment-resistant patients with major depressive disorder received computerized CR exercises in addition to 15-hour group treatment, and they showed significant improvements in sustained attention, information processing speed, verbal memory compared with the waitlist control group. Based on laboratory findings that individuals with anorexia nervosa have cognitive inflexibility, particularly difficulties with set shift tasks, Tchanturia et al. (2014) examined four patients with anoxia nervosa and after completing cognitive remediation therapy these individuals showed significant improvements in set shifting with moderate to large effect sizes.

In sum, the above programs focusing on improving cognitive functions demonstrated potentials for treating emotional disorders through the modification of attentional and other cognitive processes. Based on basic cognitive science research, the targeted mechanism of change is relatively clear and specific, and the delivery of treatment is often simple as participants complete computerized training exercises with minimal support from a therapist. However, three important questions remain unanswered. First, future investigation needs to address the causal direction between cognitive function and the etiology of psychopathology. On one hand, cognitive function may exacerbate symptoms of a specific mental disorder. On the other hand, cognitive impairments may manifest as a result of developing an emotional disorder. Second, the current literature lacks evidence for the degree to which training effects on cognitive function can transfer to distal outcomes such as psychosocial function and symptoms severity. Third, most reviewed studies contain methodological weaknesses including insufficient power and reduced internal validity due to research design (McGurk et al., 2007). Thus, future research needs to replicate these findings in randomized controlled trials with larger samples.

2.3. Attention and Mindfulness

2.3.1. Theoretical Accounts of the Relationship between Attention and Mindfulness

We have so far discussed promising evidence that attention may play a critical role in various types of psychopathology, and interventions targeting attention problems (e.g., attention bias toward negative information in depression) improve clinical symptoms (Bar-Haim et al., 2007; Bowie et al., 2013; Siegle et al., 2007). These interventions are assumed to reduce disorder-specific deficits in subsystems of attention, and such improved attentional control mediates improvements in self-regulation of emotion and other psychological problems (Siegle et al., 2007). Interestingly, a similar mechanism has been proposed for mindfulness-based interventions (Carmody, Baer, LB Lykins, & Olendzki, 2009; Chiesa et al., 2014; Shapiro et al., 2006). That is, MBIs improve the ability to maintain and shift the focus of attention with full awareness of one's goals, and this in turn reduce vulnerability to elaborative and negative thinking patterns and promote emotion regulation (Shapiro et al., 2006). Thus, we will examine the link between attention and mindfulness, especially how mindfulness training affects subsystems of attention.

As noted earlier, there exists a considerable divergence in definitions of dispositional mindfulness in the literature (Bishop et al., 2004). Among various conceptualizations of dispositional mindfulness, self-regulation of attention is generally considered a key component (Bishop et al., 2004). To highlight how mindfulness practice intersects with attention, a brief description of a breathing mindfulness exercise is provided here (Stahl & Goldstein, 2010). The client assumes a sitting position on the floor or in a chair and sustains attention to moment-by-moment changes in bodily sensations as they breathe in and out. Each time the client notices their attention wanders away from the breath, they are asked to gently bring their attention back to the object of mindfulness (i.e., breath). Throughout the exercise, the client also remains open to their experience as it unfolds without any preoccupations or judgments. This description illustrates that mindfulness practice involves several subsystems of attention and may strengthen their regulation.

The following section provides theoretical accounts of the impact of mindfulness training on three subsystems of attention: sustained attention, selective attention, and executive attentional control. First, mindfulness exercise can foster sustained attention. Sustained attention is defined as the ability to maintain one’s focus on a goal-relevant task for an extended period of time (DeGangi & Porges, 1990). During mindfulness practice, one attempts to stay focused on the breath and to notice the experience as it unfolds. The ability to maintain alertness is a critical aspect of sustained attention as it allows for the detection and registration of target information into working memory for further cognitive processing. Cultivating a goal-oriented but well-balanced alert mental state is emphasized in mindfulness practice because excessively low and high vigilance often disrupts the gating functioning of attention (Bar-Haim et al., 2007). In other words, the resulting lapse of attention (former) and restricted attentional scope like tunnel vision (latter) increases the probability to miss important information for current goals (Alexander, Langer, Newman, Chandler, & Davies, 1989; Voss, 1981).

The ability to minimize and manage distractibility is another critical aspect of sustained attention. Although alertness facilitates increased sensitivity to subtle changes in internal and external contexts, not all information that immediate environment provides carry equal value with respect to current goals, and attention can easily be shifted to goal-irrelevant information. To minimize distractibility, meditation teachers encourage two approaches (Kabat-Zinn, 1994; Stahl & Goldstein, 2010). Individuals with little meditation experience can practice staying focused on a pre-determined object of mindfulness (e.g., breath or mantra) for a prolonged period. The second approach is to learn how to reduce negative emotional reactions to or judgment of distracting stimuli. Decreased reactivity can reflect the transformation of emotionally provocative but distracting stimuli into mundane and non-salient stimuli, which in turn lower attentional capture and distractibility (Anderson, Laurent, & Yantis, 2011). When a meditator notices that the mind has wandered, they are discouraged from blaming or judging themselves for the distraction and rather encouraged to accept such experience as it and bring their attention back to the object of mindfulness.

Second, mindfulness practice has been hypothesized to promote selective attention including orienting and attention switching behavior. Orienting involves shifting attention either covertly or overtly to the source of incoming stimuli, and attention switching involves flexible attentional control by shifting attention from one object to another as the relative importance of each object changes over time (Posner, 1980; Posner

& Rothbart, 2007). For example, novice meditators can enhance selective attention by paying attention to each part of their body through guided ‘body scan’ exercise. As mindfulness practice deepens, one may expand the object of meditation to mental events (e.g., thoughts and feelings) and switch from concentrative to open meditation in which one remains open to the stream of consciousness while maintaining a ‘observer’ perspective (Thera, 2014). During open meditation, the meditator is encouraged to maintain attention in a receptive mode, to orient toward whatever conscious experience arises (orienting), and to switch attention to the next stimuli in temporal sequence without engaging any analytical and linguistic processes (attention switching). Thus, mindful people are likely to more responsive to incoming stimuli and switch attention flexibly.

Third, mindfulness practice may strengthen executive and metacognitive control. For example, a mindfulness exercise involving thoughts and feelings encourages the practitioner to make a mental note of observed phenomena using simple labels (e.g., “Here is my thought about ...…” and “I have a feeling that ......" ; Hayes et al., 1999; Linehan, 1993). Cognitive defusion exercises in ACT are also designed to learn how to observe mental events as they are, not what they stand for (Hayes et al., 1999). We surmise that these exercises can foster an ‘observer’ perspective, and thus enhanced objectivity toward personal experience increases metacognitive awareness. In addition, labeling can help reduce unnecessary engagement in elaborative and analytical processes that usually make heavy demands on attentional resources (Vanderhasselt, Kühn, & De Raedt, 2011). Considering that attention is capacity-limited (Robinson, 1995), mindfulness practice may reduce task-irrelevant and resource-demanding cognitive processes (e.g., rumination), and as a result greater attentional resources are available for higher executive control and goal maintenance.

In sum, mindfulness practice has been suggested to improve major subsystems of attention (sustained attention, selective attention, and executive attention). However, most theoretical accounts lack their specificity because they fail to explain to what degree a certain mindfulness exercise or component differentially affects subsystems of attention. The next chapter will present empirical findings that support the link between mindfulness practice and enhanced attentional control.

2.3.2. Empirical Findings that Link Mindfulness with Subsystems of Attention

We have so far provided theoretical basis for the link between mindfulness practice and enhanced attentional capacity. Now it is worthy to review empirical findings drawn from studies using objective behavioral tasks. First, there are mixed findings for the effect of mindfulness training on sustained attention. On one hand, Chambers, Lo, and Allen (2008) compared the attention and working memory between a mindfulness group who underwent a 10-day intensive meditation retreat and a wait-list control group. They found that sustained attention, measured by an internal switching task (Lo & Allen, submitted for publication), improved from pre- to post-treatment for the mindfulness group, but not for the control group. In a case-controlled study by Pagnoni and Cekic (2007), Zen meditators with more than 3 years of daily practice were compared with control participants who were matched by gender, age, and education level. Although no main effect of group was observed, the control group showed an age-related decline in both gray matter volume and poor performance in the rapid visual information processing task (Sahakian & Owen, 1992), whereas no such age effect was present in the meditator group. Likewise, Jha, Krompinger, and Baime (2007) investigated three subsystems of attention among 8-week MBSR, 1-month concentrative retreat, and meditation-naïve participants. Participants completed the Attention Network Test (ANT; Fan et al., 2002) before and after training, and a significant reduction in reaction time was observed for the retreat group but not for the MBSR and meditation-naïve groups, providing partial support for the attention-enhancing effect of mindfulness training.

On the other hand, several experimental studies reported no significant difference in sustained attention between mindfulness and control groups (McMillan, Robertson, Brock, & Chorlton, 2002; Polak, 2009; Tang et al., 2007). For example, a recent randomized controlled trial compared the effects of the MBSR and Health Enhancement Program (HEP) on sustained attention, and comparable performance on the CPT was observed (MacCoon, MacLean, Davidson, Saron, & Lutz, 2014). One possible explanation is that the duration of mindfulness training in the studies with null findings (e.g., less than 5 days) is shorter compared with the former studies (e.g., 10 days to 1 month). In addition, there is a noticeable divergence of treatment protocol, study design, statistical power, and outcome measures among studies, which makes it challenging to compare and aggregate study results. Overall, there is some support for the salutary effect of mindfulness practice on sustained attention. However, studies using brief mindfulness training may not be powerful enough to effect significant changes in sustained attention. This conjecture needs further investigation in a longitudinal study that tracks the time-dose effect of mindfulness training.

Second, there is emerging evidence suggesting that mindfulness training improves selective attention. For instance, meditation-naïve individuals were randomly assigned to one of three groups (MBSR, non-mindfulness stress reduction (NMSR), and inactive control), and results showed lower total error rates in the d2 Test of Attention (Brickenkamp, 1981) for the MBSR group compared to the other groups (C. G. Jensen, Vangkilde, Frokjaer, & Hasselbalch, 2012). Jha et al. (2007) also reported that participants in a MBSR course showed a significantly greater reduction in reaction time on the Attention Network Test (ANT) compared with participants in the retreat and control groups. In addition, Hodgins and Adair (2010) administered the Selective Attention Task (Posner, 1980) and found that meditators compared with non-meditators were faster in responding to the invalid (i.e., the cue points to a incorrect location of the target) - and neutral-cue (i.e., the cue does not carry any information about the location of the target) conditions. The results suggest that when the location cue was either misleading (invalid-cue) or uninformative (neutral-cue), meditators were able to quickly redirect their attention to the target. However, it is worth mentioning that we found two studies using brief mindfulness training reported non-significant results (Polak, 2009; Tang et al., 2007). Although these reviewed studies generally suggest the enhancement of selective attention after receiving mindfulness training, inconsistent results indicate the presence of possible confounding or moderating variables, which warrants further research.

Finally, a link between mindfulness practice and executive control has been suggested in the literature (Bishop et al., 2004; Kozasa et al., 2012; Ortner, Kilner, & Zelazo, 2007). Kozasa et al. (2012) examined performance in the Stroop Word-Color Task among regular mediators and non-mediators during fMRI scan and found no group difference in reaction time and accuracy. However, regular meditators exhibited reduced brain activation relative to non-meditators, and the authors interpreted this result as a sign of improved cognitive efficiency due to meditation practice. Further evidence is found in a longitudinal randomized controlled study that followed meditation naïve participants for 16 weeks (Moore, Gruber, Derose, & Malinowski, 2012). Participants were randomized into either meditation or wait-list group and performed the Stroop task while EEG data were being recorded. Although no significant group difference in behavioral performance was observed, the investigators reported an increase of N2 amplitudes in the left medial and lateral occipitotemporal region and a decreased P3 component in lateral occipitotemporal and inferior temporal regions. The former suggests enhanced stimulus processing and the latter indicates less use of attentional resources and thus increased cognitive efficiency. In addition, Chan and Woollacott (2007) found that Stroop interference was negatively correlated with daily meditation time, but not with lifetime meditation hours among meditators and meditation-naïve participants. Overall, empirical data on executive function are mixed, and in particular, there was inconsistency between behavioral performance and EEG data. Since executive attention is a high level of cognitive process involving multiple areas of the brain, it is possible that mediation practice may not be powerful enough to effect performance change in behavioral tasks, but still produce observable changes in neurological systems.

2.4. Attention and Neural Oscillation

2.4.1. Attention as a Selection Mechanism

The previous sections reviewed the role of attention in psychopathology and promising evidence that MBIs are effective at improving psychological conditions through improved attentional control. Although the growing amount of evidence has increased confidence of the theorized relationships among attention, both state and trait mindfulness, and psychopathology, the results of the reviewed studies are mostly corroborated by behavioral and self-reported data. Recently, research focus has shifted toward translational research that emphasizes the incorporation of basic cognitive and neuroscience research into clinical science (Insel et al., 2010). As proposed by the Research Domain Criteria (RDoC) project (Insel et al., 2010), the identification of biomarkers that underlie mental illness receives greater research attention than ever before. Thus, we will review a neuroscience account of sustained spatial attention focusing on oscillatory activity in electrophysiological data as well as behavioral performance. Furthermore, increased understanding of this neuronal process can hint at how mindfulness training improves attentional control and how existing MBIs need to be refined to enhance their efficacy.

We live in a world where external environmental conditions continuously and dynamically change, and we are constantly inundated by more information than we can process in a given moment. For example, when driving a car, a vast amount of visual information is registered in our retina each moment. Due to its limited capacity (Schneider & Fisk, 1982; Trick & Pylyshyn, 1994), our brain needs to discriminate between goal-relevant information (e.g., traffic light) and the information that does not carry any significance for our behavior (e.g., blue sky) and to select and channel such meaningful but low-level information into higher cortical areas for further processing.

Attention has been proposed to mediate the selection mechanism by which attention biases the competition for neural representation. Previous research found that attended stimuli increased neural activity of corresponding sensory areas whereas neural responses to unattended stimuli were diminished (Buschman & Kastner, 2015; Reynolds & Heeger, 2009). Using an orientation discrimination task, Li, Lu, Tjan, Dosher, and Chu (2008) manipulated stimulus contrast, orientation of the grating stimulus, and location of attention and measured blood oxygenation level-dependent (BOLD) responses from five visual areas (V1, V2, V3, V3A, and V4). The results showed an increase in baseline activity and a contrast gain effect (i.e., neurons in the visual system become more sensitive to a lower contrast threshold) when the stimulus was covertly attended. Similarly, Huang and Dobkins (2005) administered a dual-task paradigm where a rapid serial visual presentation (RSVP) task and a contrast discrimination task were simultaneously presented at the center and periphery, respectively. The authors reported that attention modulated both contrast gain and response gain (i.e., an overall increase of the contrast threshold) functions.

In addition to neuronal modulation, attention is often associated with enhanced behavioral performance in terms of detection rate and reaction time (Posner, Snyder, & Davidson, 1980). In a cueing task, shorter reaction time and higher detection rates were observed when the target stimulus appeared in a cued location compared to an uncued location (Corbetta, Miezin, Shulman, & Petersen, 1993; Posner, 1980; Prinzmetal, McCool, & Park, 2005). These results indicate that attention serves a gating function by which certain neural representations are favored over others and cognitive resources are deployed to the favored stimuli for further in-depth processing. This in turn has functional consequences to behavioral performance regarding the attended stimuli (e.g., higher detection rates).

2.4.2. Rhythmic Oscillations in Brain Activity and Behavioral Performance

One potential mechanism for attentional modulation is oscillatory neural activity (Foxe & Snyder, 2011; Kelly, Lalor, Reilly, & Foxe, 2006; Rihs, Michel, & Thut, 2007). The pioneering research on neural oscillations dates back to 1920's when Hans Berger recorded the electrical rhythmic activity of human brain and described the alpha frequency band, known as "Berger's wave" (Millet, 2002). Although there has always been a debate about the role of rhythmic brain activity, such brain waves were once theorized as "cortical idling" or mere epiphenomena of brain activity with little functional significance (Jansen, 1991; Lopes da Silva, Pijn, Velis, & Nijssen, 1997; Pfurtscheller, Stancak, & Neuper, 1996). However, recent evidence challenges this proposition and instead suggests that modality-specific periodic brain waves may carry functional relevance to underlying brain processes (Hari & Salmelin, 1997; O. Jensen, Kaiser, & Lachaux, 2007; Thut, Miniussi, & Gross, 2012).

Two frequency bands regarding neural oscillations have so far received research focus: alpha (8-12 Hz) and gamma (32-100 Hz). Alpha brain waves have been proposed to suppress processing of stimuli outside the focus of attention while gamma waves have been suggested to enhance the processing of attended stimuli (Foxe & Snyder, 2011; Fries, Reynolds, Rorie, & Desimone, 2001). To begin with, alpha synchronization has been linked to inhibition of information processing in functionally irrelevant cortical areas. For example, decreases in phasic alpha oscillations (9-13 Hz) were observed over occipital, temporal, and frontal areas when an individual was asked to name pictures both covertly (silently) and overtly (loudly) compared to when asked to passively view pictures (Salmelin et al., 1994). Similarly, Vanni, Revonsuo, and Hari (1997) reported stronger alpha band oscillations in the occipital, temporal, and parietal areas when participants attended disorganized meaningless stimuli compared to visual target objects.

Furthermore, various types of research evidence provides support that oscillations in the alpha frequency band were associated with cortical excitability (Rau et al., 2003; Sauseng, Klimesch, Gerloff, & Hummel, 2009; Zarkowski et al., 2006). Previous animal research demonstrated that local field potential (LFP) oscillations were in phase with neuronal excitability such that the phase of the oscillatory LFP cycle predicts the degree of firing rates (i.e, firing rates are high at peaks, low at troughs, and middle in between; Lakatos et al., 2005; Montemurro, Rasch, Murayama, Logothetis, & Panzeri, 2008). Scheeringa, Mazaheri, Bojak, Norris, and Kleinschmidt (2011) reported a similar relationship between the phase of the alpha frequency and the magnitude of fMRI occipital responses to a brief visual stimulus, indicating that the excitability of occipital population neurons depends on the phase of the alpha oscillations. In addition, when transcranial magnetic stimulation (TMS) was applied to the primary motor cortex, motor evoked potentials (MEPs) are more easily elicited when the TMS pulses immediately preceded a low alpha phase than a high alpha phase (Sauseng et al., 2009).

In addition to the effects of alpha oscillations on cortical processing at the neuronal level, there is preliminary evidence that rhythmic activity phasically relates to behavioral outcomes in cognitive tasks. Busch and VanRullen (2010) found that detection rates of a near-threshold luminance target were higher when the phase of ongoing 7 Hz oscillations preceding the target onset was at troughs than at peaks. Likewise, Song et al. (2014) reported alpha and beta band oscillations (8-20 Hz) in behavioral performance using a similar cueing task. In sum, there is converging evidence that attention affects the phase and amplitude of ongoing alpha activity and modulates cortical excitability, which in turn may have a functional bearing on behavioral performance.

While alpha oscillations suppress processing of unattended stimuli, gamma oscillations have been proposed to enhance in-depth information processing of attended stimuli. For instance, Shibata et al. (1999) recorded EEG from 12 human subjects during a Go-Nogo task (attention condition) and control task where they passively watched the stimuli. Greater increases in gamma band oscillations (around 40 Hz) at the Pz electrode were detected 300 ms subsequent to target onset in the attention condition. In a non-human primate study, Fries et al. (2001) recorded a subset of neurons and local field potentials (LFPs) in V4 areas while a trained macaque monkey was attending a grating stimulus presented either inside or outside the receptive field (RF). The results showed that when the stimulus appeared inside the RF, there was increased gamma-frequency (35 to 90 Hz) synchronization whereas low frequency (below 17 Hz) synchronization diminished. Moreover, gamma oscillations provide a functional advantage to behavioral efficiency (Womelsdorf & Fries, 2007). Similarly, when investigating monkey visual area V4, Womelsdorf, Fries, Mitra, and Desimone (2006) documented that attention modulated synchronization in the gamma frequency band (40-100 Hz), which in turn predicted detection speed of target color change. Taken together, attention to a task-relevant stimulus increases gamma synchronization in a corresponding cortical area and enhances behavioral performance.

We have so far presented findings about the relationship of two alpha and beta brain waves to neuronal and behavioral correlates. There is also evidence for phase-locked interactions between alpha and gamma activity, called cross-frequency coupling.

In a human magnetoencephalography (MEG) study, Osipova, Hermes, and Jensen (2008) found that gamma power (30-70 Hz) was phasically coupled to ongoing alpha oscillations (8-13 Hz). Similarly, Spaak, Bonnefond, Maier, Leopold, and Jensen (2012) examined the cross-frequency coupling between alpha and gamma bands in macaque monkeys and found that the phase of alpha oscillations in the deeper layers of Area V1 was coupled to gamma amplitude in the superficial layers. In addition, Voytek et al. (2010) recorded electrocorticography (ECoG) from two epileptic patients during visual tasks and reported that high frequency gamma activity (80-150 Hz) was phase-locked to ongoing theta (4-8 Hz) and alpha (8-12 Hz) oscillations. Specifically, gamma power peaks were coupled to theta and alpha troughs. Considering previous research demonstrating that gamma activity is positively associated with neuronal processing (Fries, Nikolić, & Singer, 2007), these results suggest that the phase of lower alpha power coincides with higher cortical processing and increased gamma activity. These findings indicate that attention-mediated alpha synchronization phasically affects levels of neuronal excitability, cortical processing, alpha and gamma activity, and behavioral outcomes.

Despite these findings, the underlying mechanism and functional relevance of oscillatory brain activity is still unclear. A number of hypotheses have been proposed in the literature, such as integration of sensory input (e.g., feature binding), coordination of communication among neural networks, and gating and routing of behaviorally relevant information (Gray, 1994; O. Jensen & Mazaheri, 2010; Thut et al., 2012; X.-J. Wang, 2010). However, these hypotheses have not been extensively tested. Thus, more research is warranted to identify how neural oscillations functionally intersect with various brain networks and behavioral performance.

2.4.3. Two Modes of Attention: Endogenous and Exogenous

When multiple stimuli are present in a visual scene, how is attention guided from one stimulus to the other? Orienting of attention is generally driven in two ways: endogenous or top-down (e.g., the driver actively searches for a traffic light) and exogenous or bottom-up (e.g., when a car cuts in front of you, your attention is automatically directed to this salient object). Although attention shifting usually entails subsequent eye movement, previous research found that directing attention without eye movement, called covert orienting, can occur (Folk, Remington, & Johnston, 1992). How endogenous and exogenous attention are executed and the competition between the two attention types is resolved is largely unknown. However, recent advances in assessment techniques (e.g., functional magnetic resonance imaging (fMRI) and high-density multi-channel electroencephalography (EEG)) have allowed for the investigation of neural activity that underlies attentional modulation of neural representations.

One potential mechanism to resolve the competition between endogenous and exogenous attention is periodic attentional sampling. Attention may be periodically switched between the attended and unattended targets, even when people are sustaining their attention on a static stimulus, and this automatic attentional sampling is related to neural oscillations (Busch & VanRullen, 2010; Fiebelkorn, Saalmann, & Kastner, 2013; O. Jensen, Bonnefond, & VanRullen, 2012). According to O. Jensen et al. (2012), alpha oscillations modulate the processing of attended and unattended stimuli in a way that attended stimuli are preferentially processed during a high alpha cycle while unattended but behaviorally less-relevant stimuli are processed when the alpha cycle is at troughs. Attempts have been made to investigate this proposition, and more empirical findings are needed. In an investigation of object-based attention, Fiebelkorn, Saalmann, et al. (2013) demonstrated that detection rates fluctuated at 8 Hz in both cued locations and uncued but same-object locations. Likewise, detections rates at the same-object locations were in anti-phase (4 Hz) with those at the different-object locations, suggesting that attended and unattended stimuli are alternately sampled with a fixed periodicity (4 Hz). Contrary to these findings, Busch and VanRullen (2010) conducted an EEG study with a spatial cueing task and reported that detection rates for attended stimuli oscillated in the theta frequency band (7 Hz). However, they did not find rhythmic fluctuations for unattended stimuli and any anti-phase relationships of detection rates between attended and unattended locations. Although these results are consistent with temporal fluctuations of behavioral performance at around 7-8 Hz, further research is needed to examine the switching of attention sampling, particularly in both endogenous and exogenous attention conditions.

CHAPTER 3

PROBLEMS AND SIGNIFICANCE

The current study aims at addressing the following problems in the attention and mindfulness literature. First, there is limited research investigating how dispositional mindfulness relates to attention that is assessed through various assessment methods. In recent decades, MBIs have been popular in clinical settings because MBIs were found to alleviate various physical and psychological problems (Kabat-Zinn, 2003; Keng et al., 2011; Khoury et al., 2013; van der Velden et al., 2015). Despite their popularity, the underlying mechanism of MBI is not clear partly due to a wide divergence in the conceptualization of mindfulness (Bergomi et al., 2013a; Bishop et al., 2004). Without objectively establishing a definition of dispositional mindfulness and its key components, it is unsolvable to determine how mindfulness training influences dispositional mindfulness and thus to refine pre-existing MBIs.

In addition to a need to conceptualize dispositional mindfulness, another fruitful avenue of research is the use of a multi-method approach. By triangulating observations from different assessment methods, one would obtain converging evidence that reveals more veridical features of dispositional mindfulness. Previous attempts have been made to examine mindfulness using behavioral tasks and neurophysiological assessment such as EEG, fMRI, skin conductance, and heart rate (see Chiesa & Serretti, 2010 for review). However, these efforts were mainly geared toward providing a descriptive account of behavioral and neurophysiological correlates rather than delineating important features of dispositional mindfulness. As noted before, most of mindfulness teachers and scholars acknowledge the importance of present-focused awareness as a key facet of dispositional mindfulness (Bishop et al., 2004). Given its conceptual overlap with attention, measured dispositional mindfulness may be correlated with neurophysiological processes of attention and observable differences in attention tasks. Once a clear relationship between dispositional mindfulness and underlying processes of attention is established, one can apply an MBI to evaluate relative dynamic associations between dispositional mindfulness and attention processes.

Second, only a few studies to date have investigated behavioral oscillations at high temporal resolution. Previous research in both animals and human subjects demonstrated that processing attended stimuli is associated with decreased alpha activity in corresponding cortical areas while increased alpha activity was observed in task-irrelevant areas (L. Wang et al., 2012; Zarkowski et al., 2006). Furthermore, the phase of alpha oscillations was found to phasically relate to neuronal excitability (Rau et al., 2003; Sauseng et al., 2009; Zarkowski et al., 2006). That is, firing rates in neurons are suppressed at a peak of the alpha phase but increased when the alpha phase is at a trough. Thus, these results suggest that attention-mediated alpha synchronization facilitates the processing of attended stimuli and route task-relevant information into higher-order processing areas through the modulation of neuronal excitability. Additionally, the phase structure of alpha rhythms has impact on behavioral performance (e.g., contrast sensitivity and stimulus detection; Voytek et al., 2010). This suggests that the time-course of behavioral performance may be entrained to the phase of these oscillatory waves.

However, previous studies using behavioral tasks and neurophysiological data are limited in that sampling rates were too coarse. In other words, although these studies varied the cue-to-target inter-stimulus interval (ISI), sampling period was too long (e.g., 100-200ms) so that these studies was not adequate to capture even low-frequency behavioral oscillations (e.g., theta and alpha). To our knowledge, there are two studies that investigated oscillations in behavioral tasks. Fiebelkorn, Saalmann, et al. (2013) studied space- and object-based attention and demonstrated that detection rates at the cued locations and uncued but same-object locations oscillated at about 8 Hz. However, they examined this effect only in an exogenous attention condition, and the location of the cue was confounded by object-based attention. A more recent study by Song et al. (2014) reported behavioral oscillations in reaction time to a cueing task where participants detected the location of the target (either left or right). However, the cue in this study was uninformative because the target appeared in the cued location at a chance level (i.e., the validity of the cue was set at 50%). In such paradigm, it is possible that participants completely ignored the cue and directed their attention to one of the possible target locations in a random manner. Given these limitations, a study is needed to randomly vary the ISI but at a high temporal resolution (e.g., sampling period of 10 ms) and to further assess behavioral oscillations in both endogenous and exogenous attention conditions.

Thus, the current study builds on previous research and addresses the problems as follows. First, we will modify a Posner cueing paradigm in a way that the cue-to-target interval systematically varies in an increment of 24 ms, and this procedure will allow us to examine temporal changes in behavioral performance as a function of fine-grained inter-stimulus interval. In addition, concurrently recorded EEG data will be transformed into frequency domain data via Fourier transform to evaluate power spectrum across frequency bands. Second, we will examine the relationship between dispositional mindfulness and both selective and sustained attention indexed by spatial cueing tasks. In particular, our analyses will evaluate whether individual differences in dispositional mindfulness are associated with rhythmic fluctuations in behavioral performance and power spectrum in neural data.

CHAPTER 4

BEHAVIORAL OSCILLATIONS IN AN ENDOGENOUS SPATIAL ATTENTION TASK (Experiment 1)

4.1. Methods

4.1.1. Participants

A total of 44 were recruited through the Psychology Experiment Sign-up System, in-class announcements, and flyers. Since age is likely to confound with outcome measures (i.e., reaction time), we only included individuals who are from 18 to 36 years old with normal or corrected-to-normal vision. As shown in Table 1, The sample consists of 8 men (18.2%) and 36 women (81.8%) with a mean age of 22.18 years (*SD* = 3.04). Participants were 59.1 % Caucasian (*n* = 26), 2.3 % African American (*n* = 1), 18.2 % Hispanic (*n* = 8), 13.6 % Asian American (*n* = 6), 4.6 % Native American or Pacific Islander (*n* = 2), and 2.3 % mixed or other (*n* = 2). Participants received extra course credit for study participation. The study protocol was approved by the Institutional Review Board at the University of Nevada, Reno.

4.1.2. Experimental Task

Behavioral data were collected using a series of modified cueing tasks (see Figure 1A for the schematic diagram). Stimuli were created using Psychophysics Toolbox Version 3.0.14 (Brainard, 1997) for Matlab. Participants were seated in a quiet room with their heads in a chin rest, and viewing distance was 57 cm. Stimuli were presented on a 22-inch (Viewsonic Graphics Series G220fb) CRT monitor (1024x768) with a refresh rate of 85Hz.

Trials began with a black fixation square (0.24° x 0.24°) at the center of the monitor on a medium gray background (128 128 128 RGB values), and fixation duration randomly varied between 500 and 1000 ms from trial to trial. The fixation was followed by a red arrow cue (1.53° x 1.53°, 0.6° off from the fixation) pointing to one of the four quadrants on the screen (Experiment1). The spatial cue appeared for 11.8 ms (1 frame), and the cue-to-target stimulus onset asynchrony (SOA) was randomized between 300 and 1,100 ms. Then, four Gabor patches (3.00° in diameter) simultaneously appeared for 11.8 ms 7.63° away from the fixation in the direction of 45, 135, 225, and 315 degree angles. Among them, only the target Gabor patch was tilted either to right or left by 7 degree angles, and participants were asked to discriminate the tilt of the target by pressing either a right or left shift key, respectively. Inter-trial interval was set to 1000 ms. The tasks consisted of that consisted of 20 practice trials and 600 test trials, and among the 600 trials, 420 trials (70%) were predictive of the target location.

4.1.3. Data Analysis

Behavioral data were analyzed with MATLAB Version 9.1 (MathWorks inc., Natick MA). Six subjects were excluded from analysis because of low performance (discrimination accuracy of less than 55 percent), ceiling effect (discrimination accuracy of greater than 90 percent), and other technical failure during experiment. Only the data from valid trials were selected, and trials with RT being greater than 2 seconds were removed from further analysis. To estimate the temporal profile of discrimination accuracy and RT as a function of cue-to-target SOA, moving averages were computed using a 35.3 ms bin (3 frames) that shifted forward in steps of 11.8 ms.

To examine periodicity in discrimination tasks, we estimated two parameters of behavioral oscillatory activity: evoked and induced power. Evoked and induced oscillations mainly differ such that the former is phase locked to the stimulus and the latter is not (David, Kilner, & Friston, 2006). On one hand, evoked oscillations represent the average power of oscillatory activity and computed by averaging time-domain waveforms across trials and converting them into frequency domain. On the other hand, induced oscillations additionally contain the non-phase-locked component of oscillatory activity and computed by applying the frequency decomposition and then averaging the amplitudes of the frequency domain data. To examine induced power, we detrended the time course data on each trial and applied the fast Fourier transform (FFT) and then averaged across trial. This procedure gave the induced amplitude spectra in each participant separately, which were then averaged across participants. To analyze evoked power, the average time-domain waveform was calculated across participants, which were then subjected to FFT.

Statistical significance of the peaks in the frequency domain data was evaluated using permutation test (Cohen, 2014). We chose permutation test because the frequency domain data were not normally distributed and the non-parametric approach does not make any assumptions about the underlying distribution. Since the null hypothesis states that no systematic temporal structure exists in discrimination performance, the trial order was shuffled, which had an effect on randomizing discrimination accuracy and RT relative to the corresponding time points in each participant. As for the observed data, the amplitude spectra of the permuted data were computed and averaged across participants, and this procedure was repeated 10000 times, leaving distributions of 10000 amplitude values across the frequencies between zero and 42 Hz. To determine significance thresholds that are equivalent to $p = .05$, 95th percentile amplitude values were selected from the distributions of each frequency bin, and the thresholds were compared with the averaged amplitude values of the observed data. To account for multiple comparisons, False Discovery Rate (FDR)-adjusted p-values ($q=.10$) were calculated via the Benjamini-Hocberg procedure (Benjamini & Hochberg, 1995).

4.2. Results

4.2.1. Rhythmic Oscillations in Behavioral Data: Induced Power

To ensure the validity of the behavioral tasks, we examined the behavioral performance. As expected, discrimination accuracy was significantly higher in the valid condition (M = 84.75%, SD = 8.70) compared to invalid condition (M = 56.54%, SD = 10.83; $t(43) = 15.08$, $p < .001$). RT was also significantly faster in the valid condition (M = 751.44 ms, SD = 168.66) compared to invalid condition (M = 1038.40 ms, SD = 335.52; $t(43) = 6.28$, $p < .001$). These results suggest that attention mediates behavioral performance in the cueing tasks such that participants experienced greater difficulty in discriminating the tilt of the target and executing a swift keyboard response when the target appeared in uncued and thus unattended locations.

To evaluate rhythmic oscillatory patterns in the behavioral data, the time course of discrimination accuracy and RT in each participant were plotted and visually inspected. As shown in Figure 2, individual subject data demonstrated fluctuations of behavioral performance over time, and these modulatory effects reached up to 70 percent. These results indicate that when a participant sustained attention at the cued location behavioral performance considerably changed depending on SOA in a given trial.

Although visual inspection of the time course effects appeared promising, it is necessary to objectively evaluate whether these fluctuations of behavioral performance reflects systematic or inherent periodicity of spatial attention or random jitters. Figure 4 illustrate the results of induced power spectral analysis. Permutation testing on the time courses of discrimination accuracy revealed that amplitudes at low Delta (1.3 Hz) and Alpha (10.4 Hz) frequency bands were found to be significant (p's = .005 and .036, respectively). In RT time courses, amplitude values at Delta (1.3~3.9 Hz), Theta (5.2 Hz), and Beta (16.7 Hz) frequency bands were above the threshold (*p*'s < .040, .048 and .023, respectively). Among these frequency bands, only the low Delta frequency (1.3 Hz) remained significant after FDR-correction in both discrimination accuracy and RT time courses.

4.2.2. Rhythmic Oscillations in Behavioral Data: Evoked Power

Next, evoked amplitude values were analyzed in order to evaluate the phase-locked components of behavioral oscillations. When the average time-domain data were visually examined (see Figure 3), both discrimination accuracy and RT changed as a function of SOA. Figure 5 demonstrated the results of evoked power spectral analysis. The results showed that amplitudes at low Delta (1.3~2.6 Hz), Theta (5.2 Hz), and Beta (16.7 Hz) frequency bands were found to be significant after FDR correction (q = .01; *p*'s < .005, *p* = .006, *p* = .012, respectively). In RT data, amplitudes at low Delta (1.3~2.6 Hz), Alpha (9.01~12.9 Hz), and Beta (16.7~18.0, 28.3~30.9 Hz) frequency bands were significant after FDR correction (q = .01; *p*'s < .005, *p*'s < .035, and *p*'s < .028, respectively).

4.3. Discussion

In summary, we analyzed non-phase-locked (induced) and phase-locked (evoked) measures of behavioral oscillations, and the results provide partial support for our hypothesis. In the induced power analysis, we found significant Delta and Alpha activity in discrimination accuracy and significant Delta, Theta, and Beta activity (uncorrected *p*'s < .05). However, FDR correction indicates that there is a good chance that these significant results represent false positives. On the other hand, there was stronger support for behavioral oscillations. After accounting for multiple comparisons, amplitudes at Delta, Theta, and Beta frequency bands for discrimination accuracy and at Delta, Alpha, and Beta frequency bands for reaction time still remained significant in the evoked power analysis.

A number of findings are worth further discussion. First, we observed a different pattern of results in the induced and evoked power analysis. The main difference between the two types of analysis is that evoked power is time-locked to the stimulus whereas induced power is not. In evoked power analysis, time-domain data were averaged across participants before FFT was applied, meaning that the phase-shifting components in individual time-domain waveforms are much attenuated after averaging. One possible explanation for non-significant induced power is that large inter-individual variability in peak frequencies could have led to non-significant findings. Previous research reported that a wide range of peak frequencies in visual attention tasks was identified (VanRullen, 2015). In our behavioral data, we found that individual peak frequency varied from person to person (see Figure 6). Although the visual inspection of individual time-domain data supported the oscillations of behavioral performance over time, such individual difference in peak frequencies lowered induced power in otherwise significant frequency bands when the frequency-domain data were averaged together.

Second and related, we observed significant peak amplitude in several frequency bands in the evoked power analysis. There is evidence that a pre-target stimulus can reset the phase of ongoing oscillatory activity (Fiebelkorn et al., 2011; Lakatos et al., 2009). As these findings suggest, the central cue in the endogenous attention task may have aligned the phase of behavioral oscillations, and in turn, common oscillatory patterns were much pronounced when the individual time-domain waveforms were averaged across participants. For example, we observed increased but non-significant induced power around 5 and 10 Hz (see Figure 4). The two waveforms are harmonics and each waveform became phase-locked to cue onset. When the individual time-domain waveforms were averaged, the signal-to-noise ratio increased due to cancellation of non-common frequency components and as a result, the common frequency component (5 Hz) was revealed in the evoked power analysis. In other words, the discrepancy found in our power analyses provides support that the onset of an endogenous cue may serve to disrupt the rhythmically ongoing time-course of attention and initiate a new phase.

Third, it is noteworthy that we demonstrated evoked power in the Theta (5.2 Hz) and Alpha (9.1 Hz) bands in discrimination accuracy and reaction time, respectively. The results are consistent with previous reports of theta (5-7 Hz) and alpha (8-12 Hz) rhythms in detection or discrimination tasks (Dugué, Marque, & VanRullen, 2015; Dugué, Roberts, & Carrasco, 2016; Dugué & VanRullen, 2014; Landau & Fries, 2012). Using EEG measurements and transcranial magnetic stimulation (TMS) over occipital cortex, Dugué et al. (2015) found that search performance significantly correlated with poststimulus alpha (~6 Hz) amplitude, and they also observed periodic interference of task performance when TMS was applied at ~6 Hz. Likewise, Dugué and VanRullen (2014) administered a color-orientation conjunction task and reported a 9 to 10 Hz oscillation in the grand-average time-course of signal detection sensitivity (d’). However, further research is needed to delineate the functional relevance of periodic sampling at various frequencies.

Fourth, despite the significant Delta oscillatory activity, we speculate that the low frequency peak does not carry much functional significance. Given that the range of SOA's was 800 ms, this sets the low frequency limit to 1.3 Hz, and this could potentially produce spurious boundary effects at this frequency (Luck, 2014). Furthermore, even if the low frequency oscillation is veridical, this could be due to a cue onset effect (Dugué et al., 2016). On one hand, reorienting attention from the cue to the cued location may reduce discrimination accuracy and increase reaction time at short SOA's, which results in a gradual positive slope in the time course of behavioral outcomes. On the other hand, return of inhibition (ROI) may produce a slow negative slope or an asymptotic trajectory at long SOA's (Posner, Rafal, Choate, & Vaughan, 1985). These mechanisms are of interest on its own, but we believe that they are functionally independent of behavioral oscillations that the current study aims to address. Likewise, we observed significant low Gamma (32.2, 36.1~40.0 Hz) activity in reaction time after accounting for multiple comparisons (q = .01; $p < .040$) in the evoked power analysis. However, we did not report this result because we smoothed the time course data using a 35.4 ms moving window. This procedure produced an effect of applying a low pass filter at 28.2 Hz (= 1000 ms / 35.4 ms), Since amplitude values at this frequency and above must have been either attenuated and distorted, we did not consider any Gamma activity in this and further analysis.

Finally, we also found peak amplitude in the Beta (12.9 and 16.7 Hz) frequency bands in both discrimination accuracy and reaction time. Although prior research demonstrated a 16 Hz oscillation that investigated EEG phase dependence in a threshold perception task (Fiebelkorn, Snyder, et al., 2013) and temporal aliasing in a motion perception task (W. A. Simpson, Shahani, & Manahilov, 2005), this is the first study to report a Beta frequency oscillation in an endogenous attention task. However, caution needs to be exercised because previous reports document that power in such higher frequencies is phase-dependent, suggesting that the phase of higher frequencies (e.g., beta) interacts with that of low frequency (e.g., delta and theta) power. Thus, further study is needed to replicate these findings.

CHAPTER 5

BEHAVIORAL OSCILLATIONS IN AN EXOGENOUS SPATIAL ATTENTION TASK (Experiment 2)

5.1. Methods

5.1.1. Participants

A total of 42 individuals participated in Experiment2 through the Psychology Experiment Sign-up System, in-class announcements, and flyers. Table 1 illustrates the demographic characteristics of the study participants. The sample consists of 12 men (28.6%) and 30 women (71.4%) with a mean age of 22.90 years (*SD* = 3.08). Participants were 57.1 % Caucasian (*n* = 24), 4.8 % African American (*n* = 2), 26.2 % Hispanic (*n* = 11), 4.8 % Asian American (*n* = 2), 2.4 % Native American or Pacific Islander (*n* = 1), and 4.8 % mixed or other (*n* = 2). Participants received extra course credit for study participation, and the study protocol was approved by the Institutional Review Board at the University of Nevada, Reno.

5.1.2. Experimental Task

Figure 1B shows the schematic diagram of Experiment 2, and the exogenous attention task in Experiment 2 is the same as the one in Experiment 1, except for the following changes (refer to Chapter 4.1.2. for the detail). In Experiment 2, the fixation was followed by a bright flash of a small white dot (0.31° x 0.31°) which appeared in one of the four possible target locations. The spatial cue appeared for 11.8 ms (1 frame), and the cue-to-target SOA was randomized between 50 and 850 ms. The task consisted of 20 practice trials and 600 test trials, and among the 600 trials, 150 trials (25%) were valid trials where the periphery cue was predictive of the target location.

5.1.3. Data Analysis

We applied the same frequency-domain analysis approaches (FFT and permutation testing) to the time-course behavioral data, and all statistical tests were corrected for multiple comparisons as in Experiment 1. Thus, a detailed description is omitted here (see Chapter 4.1.2).

5.2. Results

5.2.1. Rhythmic Oscillations in Behavioral Data: Induced Power

Before performing FFT on the time-domain data, we examined the behavioral performance. Discrimination accuracy was significantly higher in the valid condition (*M* = 82.46%, *SD* = 7.80) compared to invalid condition (*M* = 65.83%, *SD* = 13.63; t(41) = 7.15, p < .001). RT was also significantly faster in the valid condition (*M* = 798.45 ms, *SD* = 231.62) compared to invalid condition (*M* = 909.56 ms, *SD* = 266.10; *t*(43) = 4.42, *p* < .001). These results are consistent with prior research showing that attention modulates behavioral performance evidenced by higher discrimination accuracy and faster reaction time in the valid versus invalid trials (Carrasco, 2011).

Figure 7 illustrates the results of induced power spectral analysis. When the individual time-domain waveforms were examined, both discrimination accuracy and reaction time fluctuated across SOA. However, we found that none of the amplitude values reached the threshold that corresponds to the uncorrected p value of 0.05 in discrimination accuracy and RT time courses. These results provide little support for behavioral oscillations.

5.2.2. Rhythmic Oscillations in Behavioral Data: Evoked Power

Evoked amplitude values were analyzed in order to evaluate the phase-locked components of behavioral oscillations (see Figure 8). For discrimination accuracy, amplitudes at Theta (7.8 Hz), Beta (15.7 Hz) frequency bands were found to be significant after FDR correction (q = .01; *p* =.001, *p* = .004, *p's* < .004, respectively). For reaction time, amplitudes at Alpha (11.8 Hz) and Beta (14.4 Hz) frequency bands were significant after FDR correction (q = .01; *p* < .001 and *p* = .002, respectively).

5.3. Discussion

We did not find significant induced power in any frequency bands that we tested. However, we observed significant increases in evoked Theta and Alpha power in discrimination accuracy and reaction time, respectively. In a review paper on perceptual cycles, VanRullen (2016) investigated spectral distribution of 61 published articles on visual perception and reported that 10 and 7 Hz oscillations are the most common frequencies. Combined with the EEG data showing the scalp topography of perceptual periodicity, he suggested that Theta rhythm involves visual attention with increased power in frontocentral electrodes whereas the Alpha rhythm relates to sensory processing of visual information with increased power in occipital electrodes (VanRullen, 2016).

One may argue that behavioral outcomes are modulated by intrinsic neural oscillatory processes in respective cognitive domains (e.g., visual attention and low-level sensory processing). Nevertheless, the spatial resolution of EEG is weak compared to functional MRI (Cohen, 2014), and few studies report region-specific changes in EEG. Thus, systematic research programs are needed to understand the nature of spectral power in different frequency bands.

One notable finding in evoked power analysis is that frequency bands with a significantly high amplitude (i.e., theta and beta for discrimination accuracy and alpha and beta for reaction time) were the same for both endogenous and exogenous tasks. These results are consistent with a previous report showing that sustained attention in a visual target detection task alternates between same-object and different-object locations (Fiebelkorn, Saalmann, et al., 2013). Our study supports the notion that oscillatory activity phasically modulates perception in a way that even if we sustain our attention to attended stimuli, both attended and unattended stimuli are sampled at the same frequency, but alternately (O. Jensen et al., 2012). We surmise that this rhythmical attention switching between cued and uncued locations hints as how the completion between endogenous and exogenous attention is resolved. However, several task characteristics prevented us from examining the phase relationship of attention switching, such as a small number of people completing both endogenous and exogenous tasks and an unbalanced trial design for the endogenous tasks (i.e., 70% valid versus 30% invalid trials). Thus, future study needs to develop a task where both endogenous and exogenous attention are systematically manipulated.

CHAPTER 6

NEURAL OSCILLATIONS IN AN ENDOGENOUS SPATIAL ATTENTION TASK (Experiment 3)

6.1. Methods

6.1.1. Participants

Twenty seven individuals participated in Experiment3 through the Psychology Experiment Sign-up System, in-class announcements, and flyers (see Table 1 for demographic information). The sample consists of 8 men (29.6%) and 19 women (70.4%) with a mean age of 22.44 years (*SD* = 3.88). Participants were 48.1 % Caucasian (*n* = 13), 7.4 % African American (*n* = 2), 25.9 % Hispanic (*n* = 7), 11.1 % Asian American (*n* = 3), and 7.4 % mixed or other (*n* = 2). Participants received extra course credit and a $15 Amazon.com gift card for study participation. The study protocol was approved by the Institutional Review Board at the University of Nevada, Reno.

6.1.2. Experimental Task

The endogenous cueing task for Experiment3 was the same as the one in Experiment 1 (see Chapter 4.1.2.) except for the following modifications. First, the central fixation square (0.17° x 0.17°) changed color into blue, green, yellow, and red indicating the corresponding target location (left, right, either left or right, and no target, respectively) instead of using an arrow cue or white dot. Use of a less salient cue in terms of size and color would reduce cue-induced reactivity in EEG data (citation). Second, the task consisted of 450 trials, and all trials were valid so that the cue predicted the target location. Lack of invalid trials allowed for a greater number of valid trials and thus increased statistical power. Third, two Gabor patches were simultaneously presented

7.63° left and right to the fixation cue. A reduced number of possible target locations allowed for a simpler explanation of the results and the effect of reducing the number of total trials. Fourth, SOA was set to 1 second in order to equate corresponding EEG epochs across trials. Fifth, the discrimination threshold (70% overall discrimination accuracy) was determined individually using a staircase procedure, and the tilt angle of the target was adjusted accordingly. Although this calibration procedure would prevent any meaningful between-subject comparisons of overall discrimination accuracy and RT, making an individual adjustment of task difficulty resolved ceiling and floor effects and contributed to retaining more cases.

6.1.3. EEG Recordings and Pre-processing

The EEG was continuously recorded via a 256 channel HydroCel Geodesic Sensor Net and EGI Net Amps Bio 300 amplifier (Electrical Geodesics Inc., Eugene, OR) while participants are performing behavioral tasks. The EEG data were sampled at 1,000 Hz and collected and digitized using EGI Netstation Acquisition 5.0 software. Before frequency analyses, the raw EEG data were pre-processed via EGI Netstation Tools. EEG signals were band-pass filtered between 0.1 Hz and 50 Hz with a rolloff of 0.3 Hz and 10Hz, respectively, and epoched from the cue onset to the target onset (100 ms). An epoch with eye blink, eye movement, or more than 10 bad channels was marked as a bad trial and excluded from further data analysis. The remaining bad-channel data in good trials were replaced by a bad channel replacement tool with spherical spline interpolation of the neighboring channel values and re-referenced to the average of the 256 censors. Participants whose percentage of bad trials were greater than 30% were excluded from the study.

6.2. Results

6.2.1. Behavioral data

To evaluate behavioral performance in Experiment 3, we computed individual means for discrimination accuracy and reaction time depending on cue types and conducted paired t-tests. For discrimination accuracy, there was no significant difference between the Left (cue to the left of fixation) and Right (cue to the right of fixation) conditions ($t(26) = 1.35$, $p = .190$). Likewise, discrimination accuracy for the data combining the Left and Right conditions ($M = 83.61\%$, $SD = 9.98$) was not significantly different from that for the Either Direction (cue was not predictive) condition ($M = 82.10\%$, $SD = 9.59$; $t(26) = -1.72$, $p = .098$). On the other hand, participants responded significantly faster when cued to the right of fixation ($M = 619.88$ ms, $SD = 108.92$) than cued to the left ($M = 638.88$ ms, $SD = 111.92$; $t(26) = 2.56$, $p = .017$). Reaction time was also significantly lower for the data combining the Left and Right conditions ($M = 629.50$ ms, $SD = 108.67$) compared with the Either Direction condition ($M = 638.99$ ms, $SD = 108.77$; $t(26) = 2.27$, $p = .032$).

6.2.2. EEG: Induced Power Analysis

Figure 9 through 14 show topographic maps and induced power spectral analyses of the EEG data from Experiment 3. To test the difference in index values of each comparison, one-sample t-tests were conducted at each electrode using the FDR corrected threshold of $q = .01$. First, we found little support for lateralization. As shown in Figure 9, few index values for the Left (cue to the left of fixation) vs. Right (cue to the right of fixation) condition were significant. Second, we examined index values in Left vs. No Target (Figure 10), Right vs. No Target (Figure 11), and Either Direction (target appeared in either location at 50%) vs. No Target (Figure 12) conditions, and we observed decreased delta and theta power in frontocentral electrode cites. Although there was an indication for increased beta and low gamma power in frontotemporal electrode cites, they failed to remain significant after FDR correction. Finally, we examined index values in the Either Direction vs. Left (Figure 13) and Either Direction vs. Right (Figure 14) conditions, but none of electrode cites were found to be significant.

6.2.3. EEG: Evoked Power Analysis

Topographic maps and t statistics for evoked power analyses are presented in Figure 14 through 19. When index values for the Left vs. Right condition (Figure 14) were assessed, none of the electrode sites were found to be significant. Next, we examined index values in Left vs. No Target (Figure 15), Right vs. No Target (Figure 16), and Either Direction vs. No Target (Figure 17) conditions, and the results suggest increased power in almost all electrode sites across all frequency bands in the No-target condition relative to all other conditions. Lastly, index values were evaluated for the Either Direction vs. Left (Figure 18) and Either Direction vs. Right (Figure 19) conditions. Globally increased delta, beta, and low gamma power was observed in the Either Direction condition relative to the Left and Right condition.

6.3. Discussion

In the current experiment, we investigated whether visual spatial attention modulates neural synchrony in our EEG data. We observed significant power spectral suppression in frontocentral electrodes in Delta and Theta bands when participants' covert attention shifted either to the left or right target location compared with no-target condition. This means that when participants engaged visual spatial attention to the cued location, amplitudes in low frequency bands decreased relative to when their attention was disengaged from the task. This result is consistent with previous research showing widespread suppression below 50 Hz during the cue-to-target delay in a motion discrimination task (Siegel, Donner, Oostenveld, Fries, & Engel, 2008). In contrast, we observed a weak enhancement of Beta and low Gamma activity in lateral frontal and temporal electrode cites, and this Delta and Theta suppression and Beta and low Gamma enhancement existed across all comparisons in relation to the non-target condition. Cross-frequency coupling literature suggests that low frequency activity associated with deep-sleep states are suppressed during attention tasks while Gamma activity that is responsible for active sensory processing increases (Fries et al., 2001; Schroeder & Lakatos, 2009).

Unlike previous reports (Sauseng et al., 2005; Thut, Nietzel, Brandt, & Pascual-Leone, 2006), however, we found no hemisphere-specific lateralization in Alpha power. Previous studies report Alpha power suppression in the hemisphere contralateral to the cued location, which is considered increased sensory excitability in the location where the target will appear. This difference can be attributed to task-specific difference such that in our cueing paradigm SOA was fixed to 1 second and the central cue was predictive of the target location in all trials whereas other studies used variable SOA's and set cue predictability to less than 100 percent. Since the timing of cue onset was highly predictable in our experiment, it is possible that participants did not monitor the cued location for the entire cue delay, which led to weak Alpha suppression.

CHAPTER 7

ATTENTION AND DISPOSITIONAL MINDFULNESS

7.1. Methods

7.1.1. Participants

A total of 86 individuals who participated in Experiment 1 (*n* = 44) and Experiment 2 (*n* = 42) were include in data analysis. Table 1 shows demographic information and meditation experience of the sample.

7.1.2. Questionnaires

Mindfulness Attention Awareness Scale (MAAS). The MAAS (W. Brown & R. Ryan, 2003) is one of the most commonly used questionnaires that assesses how frequently one is *not* paying attention to their thoughts, feelings, physical sensations, and tasks at hand (Sauer et al., 2013). This brief instrument consists of 15 items that are rated on a 6-point Likert scale ranging from 1 (*almost always*) to 6 (*almost never*) with high scores representing heightened levels of dispositional mindfulness. Sample items include “I find it difficult to stay focused on what’s happening in the present,” “It seems I am ‘running on automatic’ without much awareness of what I’m doing,” and “I find myself preoccupied with the future or the past.” The MAAS has been validated in college population, and the internal consistency is adequate (Cronbach’s alpha = .82-.87), and test-retest reliability was acceptable (intraclass correlation coefficient [ICC] = .81; W. Brown & R. Ryan, 2003; MacKillop & Anderson, 2007). The MAAS has been extensively used in research to investigate dispositional mindfulness in relation to its neural correlates (Brown, Goodman, & Inzlicht, 2012; Creswell et al., 2007; Way, Creswell, Eisenberger, & Lieberman, 2010), behavioral performance (Kee & Liu, 2011), various psychological constructs (Bränström, Duncan, & Moskowitz, 2011; Peters, Erisman, Upton, Baer, & Roemer, 2011), and treatment outcome (Chiesa & Serretti, 2009; Shapiro, Brown, Thoresen, & Plante, 2011). A total score was computed by summing individual item scores.

Five Facets Mindfulness Questionnaire (FFMQ). The FFMQ (Baer et al., 2006) was created by factor analyzing a 112-item pool derived from five validated mindfulness questionnaires. The 39 items of the FFMQ are rated on a 5-point Likert scale ranging from 1 (*never or very rarely true*) to 5 (*very often or always true*). Sample items include, “I pay attention to how my emotions affect my thoughts and behavior,” “I’m good at finding words to describe my feelings,” “I am easily distracted,” and “I criticize myself for having irrational or inappropriate emotions.” In Baer et al.’s study (2006) using large college samples, five factors (i.e., Observing, Describing, Acting with Awareness, Non-judging of Experience, and Non-reactivity to Internal Experience) were identified with mindfulness being a second-order factor. The FFMQ was shown to have good psychometric properties, such as internal consistency (Cronbach’s alpha for the subscales = .75-.91), convergent and discriminant validity, and incremental validity (Baer et al., 2006). The scale has been shown to co-vary with mindfulness training (Carmody et al., 2009) and meditation time (Carmody & Baer, 2008) and to differentiate meditators and non-meditators on performance in attention tasks (Josefsson & Broberg, 2011). Although the FFMQ provides the broadest coverage of mindfulness facets, items on the Observing factor may function differentially depending on individual’s mindfulness experience (Van Dam, Earleywine, & Danoff-Burg, 2009). Thus, the FFMQ data were analyzed using sub-scale scores that were computed by summing the individual item scores in each sub-scale.

Adult ADHD Self-Report Scale (ASRS). The ASRS (Kessler, Adler, et al., 2005) is a 6-item screener of adult attention-deficit hyperactivity disorder (ADHD). The respondent is instructed to rate how often they have experienced each item over the past 6 months using a scale ranging from 0 (*never*) to 5 (*very often*). Sample items include "How often do you have trouble wrapping up the final details of a project, once the challenging parts have been done?" "How often do you have difficulty getting things in order when you have to do a task that requires organization?" and "How often do you have problems remembering appointments or obligations?" Scoring was performed by counting the number of items whose ratings are equal to or greater than 2 (Item 1, 2, and 3) or 3 (Item 4, 5, and 6), and the total score of 4 and above indicates ADHD diagnosis. The ASRS has shown acceptable sensitivity (68.7%), and excellent specificity (99.5%), total classification accuracy (97.9%), and κ (0.76; Kessler, Adler, et al., 2005). The ASRS has been used in college samples and in a national survey (Gropper & Tannock, 2009; Kessler et al., 2006; Yen, Yen, Chen, Tang, & Ko, 2009).

7.1.3. Experimental Tasks

Before completing the cueing tasks in Experiment 1 and Experiment 2, participants answered questionnaires on dispositional mindfulness, ADHD symptomatology, and meditation experience. To evaluate how the five facets of dispositional mindfulness relate to the time-domain and frequency-domain behavioral data, we conducted correlation analyses for Experiment 1 and Experiment 2 separately, and FDR correct was applied to account for multiple comparisons (see Chapter 4.1.2. and Chapter 4.1.3. for the detail).

7.2. Results

7.2.1. Preliminary Analysis

Before conducting statistical tests on the relationship between behavioral performance in the cueing tasks and dispositional mindfulness, we examined the behavioral data in order to check for any moderating effects of gender, age, and possible ADHD diagnosis. No significant effects of gender were found for discrimination accuracy ($t(42) = 1.36$, $p = .182$ for Experiment 1 and $t(40) = 0.99$, $p = .331$ for Experiment 2) and reaction time ($t(42) = -0.39$, $p = .700$ for Experiment 1 and $t(40) = -1.49$, $p = .145$ for Experiment 2). To evaluate age effects, Pearson correlation coefficients were examined. The results showed no significant effects of age on discrimination accuracy ($r = 0.074$, $p = .633$ for Experiment 1 and $r = 0.027$, $p = .137$ for Experiment 2) and reaction time ($r = 0.054$, $p = .733$ for Experiment2). Although we found that age was positively correlated with RT in Experiment 1 ($r = 0.364$, $p = .015$), the result no longer remained significant after excluding one the oldest participant with the slowest RT ($r = 0.127$, $p = .419$). Finally, we compared individuals with and without possible ADHD diagnosis (screened with the ASRS; Kessler, Adler, et al., 2005). No significant effects of ADHD were found for discrimination accuracy ($t(42) = 0.15$, $p = .879$ for Experiment 1 and $t(40) = 0.27$, $p = .788$ for Experiment 2) and reaction time ($t(42) = -0.48$, $p = .633$ for Experiment1 and $t(40) = -0.04$, $p = .972$ for Experiment2). Since no support was found for gender, age, and possible ADHD diagnosis, these variables were excluded from further analysis.

7.2.2. Behavioral Performance

We evaluated whether the five subscale scores of the FFMQ and the total score of the MAAS were correlated with behavioral performance. Table 2 shows descriptive statistics and correlations among study variables. Correlation analysis showed that reaction time was significantly correlated with the Observe subscale score in both endogenous and exogenous attention tasks, but in opposite directions (*r* = -.32, *p* = .038 for Experiment 1 and *r* = .47, *p* = .002 for Experiment 2). After FDR correction (*q* = .10) was applied, only the correlation in the exogenous task remained significant suggesting that individuals with higher levels of observation skills were slower at responding to the exogenous cue compared to those with lower levels of dispositional mindfulness. Discrimination accuracy in Experiment 1 was negatively correlated with the Non-react subscale score of the FFMQ (*r* = -.33, *p* = .034). This result was somewhat surprising because mindfulness training has been shown to enhance attentional control. However, the FDR-corrected p value (*p* = .234) was no longer significant, indicating that the observed bivariate correlation was likely to be due to chance.

7.2.3. Induced Power

Next, we examined whether levels of dispositional mindfulness related to amplitudes of oscillatory activity in behavioral performance. The frequencies that were found to be significant at uncorrected *p* < .05 (see Section 5.1.) were identified, and we conducted correlation analysis on the five subscale scores of the FFMQ and power spectral data at these identified frequencies. Statistical significance was determined after FDR correction for multiple comparisons (*q* = .10), and correlations are shown in Figure 9 through 11. For induced power, we examined correlations at 10.4 Hz for discrimination accuracy and 5.2 and 16.9 Hz for reaction time in Experiment1. However, amplitude values were not significantly correlated with any of the five FFMQ subscale scores (see Figure 21).

7.2.4. Evoked Power

For evoked power, the Act-with-Awareness and Non-judge facets were positively correlated with the Beta frequency band (16.9 Hz; *r* = .34, *p* = .024 and *r* = .40, *p* = .007, respectively) in discrimination accuracy for Experiment 1, and the correlation with the Non-judge facet remained significant after FDR correction (*q* = .10). The Observe facet was negatively associated with the Beta frequency band (13.0 Hz, *r* = -.39, *p* = .009), and the Describe facet showed a significant correlation with amplitude values at 18.2 Hz (*r* = -.37, *p* = .013) in reaction time for Experiment 1 (see Figure 22). Additionally, the Act-with-Awareness facet was negatively correlated with amplitude values at 7.8 Hz (*r* = -.33, *p* = .031) in discrimination accuracy for Experiment 2 (see Figure 23).

7.3. Discussion

We observed a positive correlation between the scores of the Observe facet and reaction time in the exogenous attention task. In other words, those who are highly observant of their experience were slower to respond salient sensory information. At first sight, this result appears counter-intuitive because slower reaction time generally indicates inefficient processing of information. However, it is noteworthy that the exogenous cue in Experiment 2 was not predictive of the target location. Under this situation, the optimal task strategy is simply to ignore the location cue and conserve attentional resources for the upcoming target. On the other hand, we found a near-significant negative correlation between the scores of the Observe facet and reaction time in the endogenous attention task. Compared to participants with lower Observing subscale scores, participants who scored high on the Observing subscale scores may be more attentive to the predictive endogenous cue and less vulnerable to distraction or task-irrelevant stimuli. These interpretations are consistent with both theorized relationship between the variables in mindfulness literature and prior research demonstrating that the MBSR group shower higher orienting abilities in the Attention Network Test (ANT) compared with the meditation naïve group (Chiesa, Calati, & Serretti, 2011; Jha et al., 2007).

Next, we observed some significant correlations between FFMQ subscale scores and evoked power. To our knowledge, this is the first study to investigate the relationship between dispositional mindfulness and behavioral oscillations. Since the present study is exploratory in nature and limited research exist on rhythmic cycles of behavioral performance, significant caution needs to be exercised to interpret these results. Theoretically, two FFQM subscales are particularly relevant to the current study: Observe and Act-with-Awareness. The former concerns perceptual sensitivity and alertness (e.g., “I pay attention to sensations, such as the wind in my hair or sun on my face”), and the latter involves the ability to focus attention and executive functioning (e.g., “When I do things, my mind wanders off and I’m easily distracted”). Individuals who score high on these sub-scales are expected to perform well on a discrimination task because enhanced perceptual sensitivity would help judge the tilt of the target, and focused attention would minimize distraction during the task. Neurophysiologically, spatial attention is often associated with the ability to suppress irrelevant information, and Alpha-band oscillatory activity is indicated to underlie the suppression of processing in cortical regions (Foxe & Snyder, 2011). Additionally, previous EEG studies on dispositional mindfulness reported decreased alpha amplitude among Zen meditators (Kasamatsu & Hirai, 1966; Murata et al., 2004). In the evoked power analysis in the exogenous attention task, we observed a negative correlation between the Act-with-Awareness facet and amplitude values in the Alpha frequency band. It is possible that the observed results may support the relationship between Alpha suppression and the mindful facet regarding focused attention. However, the finding did not survive FDR correction, and further investigation is needed.

Finally, it is worth mentioning that we excluded data analysis on the relationship between EEG synchronization and self-reported dispositional mindfulness. Our experiment was not enough powered to detect even a large effect. We conducted a power analysis, and the result showed that our dataset with 27 participants is sufficient to detect a minimum of $r = .52$ at $\alpha = .80$. However, overall weak correlations with mindfulness facets in Experiment 1 and Experiment 2 and method difference suggest a weak statistical power, which is highly likely to yield spurious findings. However, we recommend future attempts to examine the relationship between levels of dispositional mindfulness and evoked EEG activity in a spatial attention task. Given the individual variability in Alpha peak frequency in EEG, a future study may benefit from investigating the effect of dispositional mindfulness on such peak frequency.

CHAPTER 8

GENERAL DISCUSSION

8.1. Burgeoning Field of Mindfulness Research on its Relation to Attention

The current study presents support that levels of dispositional mindfulness are associated with spatial visual attention such that higher observing skills indicated enhanced attentional control in terms of sustained attention, orienting, and active suppression of task-irrelevant information. This result is consistent with previous reports demonstrating that mindfulness training enhanced various cognitive capacities (Chiesa et al., 2011). However, there exist studies showing non-significant differences in sustained attention between experienced meditators and non-meditators or in randomized controlled studies (McMillan et al., 2002; Polak, 2009; Tang et al., 2007). These mixed findings suggest the presence of moderating variables and a need to address methodological weaknesses in future research.

First, a systematic and meta-analytic approach is needed to examine the dosage effect of MBIs. Although there are a large number of studies examining the effects of MBIs, dosage effect has not been firmly established. Generally, the duration of MBIs varies from 10-minute mindfulness induction to an over 3-month-long intensive retreat (Braboszcz et al., 2013; Dickenson, Berkman, Arch, & Lieberman, 2012). Since practice duration is generally assumed to correlate with one's level of mindfulness, an MBI with a shorter duration may not be as potent as a longer mindfulness program. In other words, studies using a brief MBI are less likely to produce significant results. However, this assumption needs to undergo empirical testing which can reveal incremental effects of MBIs on cognitive functioning by program duration.

Second consideration for methodological improvement is that participants may not acquire mindfulness skills in a linear fashion and respond to mindfulness training differently. Some studies used a pre-recorded audio or video recording (McMillan et al., 2002; Watier & Dubois, 2016), but it is possible that meditation naïve participants did not understand the instructions or were not granted an opportunity to ask questions.

Similarly, some participants could have utilized only a small amount of attentional resources during mindfulness training without paying full attention to their experience. This may be sufficient to notice granular changes in sensations from internal and external stimuli, but not necessarily strengthen their ability to stay focused and detect nuanced or subtle changes. Failure of such quality control over the mindfulness program could have reduced MBI's effects and produced inconsistent results.

Third, future research needs to focus on elucidating mechanisms of change by which MBIs improve attentional control. We found that many studies on MBIs lack specificity without providing cogent rationale for the selection of certain types of mindfulness practice and attention tasks. Literature documents significant heterogeneity among MBIs, and different mindfulness programs have their unique training goals and methods (Sauer et al., 2013). For example, open monitoring mindfulness meditation encourages practitioners to expand their awareness to various internal and external stimuli and the moment-to-moment experience as they come and go. On the other hand, practitioners are asked to pay full attention to the object of meditation (e.g., image, sound, mantra) during focused attention meditation. Chiesa (2013) suggests that the former promotes executive function (e.g., meta-awareness of one's attention and cognitive flexibility in shifting attention from one stimulus to the other) while the latter improves the ability to sustain attention without distraction. Since a significant amount of mindfulness studies already exist, it may be a fruitful attempt to identify and analyze critical components of mindfulness utilized in each MBI and compare the results by types of attention tasks.

Fourth, a valid and reliable conceptualization of mindfulness needs to be established. Brown and Ryan (2003) pointed that little consensual agreement on the operational definition of mindfulness exist among researchers. Without such definition, studies based on different conceptualizations are not directly comparable, and this will increase the chance to produce inconsistent findings. On a similar note, the development of objective measures of mindfulness is required. The status quo is that majority of studies on mindfulness and MBIs rely on self-report questionnaires. Not only these questionnaires lack stable factor structure, but also they capture subjective report of trait or state mindfulness, which may not be closely tied to substantive aspects of mindfulness. Recent studies using diverse assessment methods such as neuroimaging techniques, EEG, and behavioral tasks are encouraging, and the results from these studies can be useful to triangulate mindfulness and reduce measurement errors in current assessment methods.

Despite the recent growth in mindfulness research, several key methodological issues such as questionable internal validity, poor quality control of MBIs, and lack of objective assessment measures of mindfulness hamper the progress of our understanding. It may be true that diverse methods of mindfulness training create divergent pathways to outcomes and increase the accessibility to individuals with their own training goals and needs. However, when the goal of research lies in increasing our understanding of the underlying mechanism, establishing and testing a hypothesized relationship among different aspects or components of mindfulness, training methods, and cognitive outcomes is the next step for future research.

8.2. Two Subsystems of Attention and Psychopathology

In addition to mindfulness, the current study investigated two subsystems of attention: exogenous and endogenous attention. One primary function of attention is to selectively orient to task-relevant information and when needed, to maintain focus for further processing, and this provides a functional advantage in terms of accuracy and processing speed (Carrasco, 2011). The source of attended information can be both external (e.g., someone calls your name) and internal (e.g., feeling hunger or having a spontaneous thought about the current situation). Regardless of the locus of information, attention can be automatically (exogenously) or voluntarily (endogenously) summoned (Chica, Bartolomeo, & Lupiáñez, 2013). Goal-relevant information is relayed to higher cortical areas for further cognitive processing, and non-relevant information is actively suppressed (Buschman & Kastner, 2015). If such gatekeeping function of attention constantly operates with and without much awareness (i.e., endogenous and exogenous attention, respectively), it is conceivable that a mechanism may exist that resolves the competition between these two attention systems.

In our daily living, attention plays a pivotal role in orienting sensory modalities through orienting to the source of information, filtering in goal-relevant information, and influencing other cognitive and emotional processing. When one develops a deficit in the ability to control attention, its negative impacts become apparent. For instance, attention deficit hyperactivity disorder (ADHD) is characterized by difficulty in staying focused, proneness to distraction to task-irrelevant events, constant activity such as fidgets and taps, and impulsive behaviors (American Psychiatric Association, 2013). These individuals have trouble organizing a complex task with frequent distractions and experience forgetfulness due to attention lapses during encoding of information. Furthermore, deficits in attentional control are common throughout the spectrum of mental disorders. Individuals with anxiety disorders have been shown to be highly sensitive to anxiety-provoking stimuli (Reiss, Peterson, Gursky, & McNally, 1986). For example, a patient with phobia to insects may experience excessive emotional and physiological reactions even when a topic of insects is brought up during a casual conversation. Similarly, depressed individuals may have trouble disengaging their attention away from negative information and cannot stop rumination (Siegle, Steinhauer, Thase, Stenger, & Carter, 2002).

Since attention problems are common across psychological disorders, it is possible that attentional control may underlie the mechanisms of psychopathology. One may argue that attention problems are mere epiphenomenon of a psychological disorder instead of causally relating to psychological symptoms. Here we argue that attention plays a central role in psychopathology and presents preliminary evidence. Let's illustrate how two subsystems of attention can map onto the existing theoretical models of psychological disorders. As discussed early, exogenous attention is driven by salient stimuli whereas endogenous attention is considered under voluntary control and directed towards goal-relevant information in a given moment (Chica et al., 2013). When these subsystems of attention are dysregulated, disruption of a regulatory system of emotion often co-occurs or follows.

For example, PTSD is often conceptualized based on learning theory, particularly focusing on stress responding and fear conditioning (Cain & Sullivan, 2016). That is, traumatic experience such as rape and mugging produces traumatic stress response including re-experiencing of the trauma, avoidance of trauma-related cues, and hyperarousal (American Psychiatric Association, 2013), and these trauma symptoms typically subside within days or weeks after the trauma (Rothbaum & Davis, 2003). However, those who develop PTSD fail to extinguish post-traumatic stress response and over-generalized fear conditioning (i.e., topographically similar but non-dangerous stimuli trigger stress response) worsens trauma symptomatology (Lissek & van Meurs, 2015). In other words, attention bias in PTSD indicates the dysregulation of exogenous attention in such a way that goal-irrelevant information falsely activates the exogenous attention system, which in turn disrupts the endogenous attention system and aggravates emotional distress.

A number of neuroscience studies have suggested hyperactivation and dysregulated functional connectivity of the amygdala as a biomarker (El Khoury-Malhame et al., 2011; Rabellino et al., 2016). These studies demonstrated that changes in amygdala activity were associated with the processing of emotional stimuli and symptom severity among individuals with PTSD (El Khoury-Malhame et al., 2011; Rabellino et al., 2016). Consistent with these results, it was found that the amygdala plays a critical role in biasing attentional resources and enhancing the processing of sensory information from salient events by projecting signals to visual cortex and fronto-parietal attention regions (Amaral, Behniea, & Kelly, 2003; Pourtois, Thut, de Peralta, Michel, & Vuilleumier, 2005). Interestingly, Liddell et al. (2005) demonstrated that a neural network involving superior colliculus and pulvinar as well as amygdala was activated by subliminally presented fearful stimuli, indicating that attentional bias in exogenous attention may operate even without awareness. This result may explain chronic hypervigilance symptoms of PTSD that the patient complains without identifying their triggers.

In contrast to bottom-up influence of exogenous attention, recent findings have shown that top-down factors of attention such as goals and expectations causally relate to psychological problems (see Sussman, Jin, & Mohanty, 2016 for review). For instance, individuals with anxiety have a tendency to misinterpret ambiguous information as threatening and to overestimate the probability that a negative event will occur (Grupe & Nitschke, 2013). These cognitive biases can misguide the endogenous attention into searching for potentially threatening stimuli even when active searching is not necessary. Furthermore, since one needs to hold the mental representation of search targets that are aversive, threating, and unpleasant, the individual is likely to experience a more negative emotional state. Similarly, people with generalized anxiety disorder (GAD) often have a tendency to regard worry as an adaptive and effective coping approach to potential threats or dangers (Cartwright-Hatton & Wells, 1997). Such positive evaluation of worry may bias their endogenous attention system and sensitize these individuals to negative future events.

So far we presented evidence that both exogenous and endogenous attention are associated with psychopathology. Although attention provides a perceptual advantage of enhancing the processing of attended stimuli, the dysregulation of these two subsystems of attention can contribute to psychological problems. Dysfunctional perceptual priotization inundates people with distracting information or misguides their attention to goal-irrelevant stimuli. Future research should aim to further elucidate the causal link between these attention subsystems and psychopathology, especially how top-down and bottom-attention interacts as a function of disorder-specific symptomatology.

8.3. Impaired Attentional Control and Emotion Dysregulation

We have so far discussed the association between dysregulated subsystems of attention and psychopathology. In this section, we aim to further explain how impairment in attentional control disrupts the ability to regulate emotion and develops psychological problems. For example, it is noteworthy that systems involving attention and emotion are closely related at the neural, behavioral, and cognitive levels (Ochsner & Gross, 2008; Luiz Pessoa, 2008). According to this view, the long-held notion that brain areas responsible for attentional and emotional processing are separate and highly localized is losing ground. Instead, these systems dynamically interact and operate in an integrated manner through brain networks (Luiz Pessoa, 2008). For instance, amygdala has been known as a ‘fear center’ concerning emotional processing, particularly fear conditioning. Patients with a bilateral amygdala lesion show difficulty recognizing fearful expression (Aggleton, Everitt, Cardinal, & Hall, 2000). Despite the general view that amygdala serves to process emotional stimuli automatically and independently (Vuilleumier, Armony, & Driver), neuroimaging studies demonstrated that amygdala responses did not change regardless of the valence of emotional stimuli when participants were engaging in a competing task, indicative of the modulation of amygdala activity by top-down control of attention (L Pessoa, McKenna, Gutierrez, & Ungerleider, 2002; Vuilleumier, Armony, & Driver, 2003). A similar integration between attention and emotion is also found in the anatomy of the hypothalamus such that the hypothalamus receives inputs from a wide variety of sensory modalities as well as cerebral cortex, and innervates motor systems to exhibit reflexive motivated behaviors (e.g., defense; Risold, Thompson, & Swanson, 1997). These results indicate that our emotional and cognitive systems are closely integrated and influence each other by a reciprocal feedback loop.

In addition to such anatomical and functional overlap between attention and emotion systems, experimental studies hint at the role of attention bias in negative affectivity and emotional disorders. For example, individuals with social phobia have a tendency to shift attention toward the self by focusing on interoceptive feelings of anxiety and fear of embarrassment and humiliation when they are exposed to social situations. In Wells and Papageorgiou (1998)'s study, participants who meet the diagnostic criteria for social phobia were trained to shift their attention focus away from self-focused concerns and toward external social environment (e.g., people's verbal and non-verbal reactions). The results showed that external attention focus led to a reduction of social phobia symptomatology and associated maladaptive beliefs. Similarly, MacLeod, Rutherford, Campbell, Ebsworthy, and Holker (2002) developed a computerized attention modification program using a dot probe task, wherein the contingencies of whether the probe would follow neutral or threatening cue was manipulated. The results showed that participants who were trained in shifting attention toward the threatening cue reported higher levels of anxiety and depression symptomatology in response to a stressful task compared to those who were trained in attending to the neural cue. These results provide strong support that attention bias is causally important in mediating the ability to regulate emotion.

Emotion regulation has been defined as the ability to modulate which emotions to have and when and how to experience and express these emotions in the context of a person-situation transaction (Gross, 1998). A process model of emotion regulation posits a sequence of five processes that can be the target of emotion regulation strategies: situation selection, situation modification, attentional deployment, cognitive change, and response modulation (Gross & Thompson, 2007). While the first four processes occur before full-blown emotional responses are formed (antecedent-focused), response modulation concerns how to modify the already generated emotional response (response-focused) to meet one's emotional goals or needs.

Among these processes, impaired attentional control affects situation selection, situation modulation, as well as attentional deployment. Attention affects whether or not one enters a situation where experiencing unwanted emotion is expected. For instance, individuals with an anxiety disorder often report heightened sensitivity to a fear-provoking situation and exaggerated emotional responses than the occasion warrants. Their attention bias appears to provide an advantage to situation selection such that anxious individuals can quickly detect cues that are associated with potential threats, which allows them to avoid certain places, people or situations that can lead to negative consequences. However, anxiety literature suggests that activation of the fear structure through adequate exposure to anxiety-provoking stimuli is critical in the treatment of anxiety disorders (Rauch & Foa, 2006). In other words, repetitive and rigid use of situation selection (e.g., avoidance) as a primary emotion regulation strategy has an iatrogenic effect and contributes to the maintenance of anxiety disorder. Thus, correction of attention bias may facilitate more adaptive use of situation selection strategies (e.g., gradually exposing oneself to a fearful situation instead of avoiding it regardless in order to reduce the symptoms of anxiety disorder).

Next, situation modification involves changing the situation directly in order to alter emotional experience. Individuals with specific phobia (e.g., fear of insects) frequently scan the environment for potential threats (e.g., bugs) in an effort to cope with a fear-provoking situation (e.g., escape the scene). Although their attention bias may increase perceptual sensitivity to insects and other fearful stimuli (MacLeod et al., 1986), such bias disrupts one's ability to regulate emotion. For instance, since attention is limited capacity (Trick & Pylyshyn, 1993), those who stay vigilant for potential threats may reduce attentional resources available for other cognitive processes, and thus they have difficulty utilizing information that is threat-irrelevant but significant to their current goals. In other words, stimulus-driven attention bias comes at the expense of goal-directed, top-down control of attention and results in diminished self-regulation of emotion (Eysenck, Derakshan, Santos, & Calvo, 2007). Furthermore, such unsuccessful attempt may increase negative affectivity, induce a low sense of self-efficacy, and reinforce avoidant behavior in the future.

A growing body of research suggests emotion regulation as a transdiagnostic process that cuts across various psychological disorders, and maladaptive use of emotional regulation strategies such as rumination, worry, and avoidant behavior contributes to the development and maintenance of psychopathology (Aldao & Nolen-Hoeksema, 2010; Kring & Sloan, 2009). Furthermore, there is evidence that impaired attentional control can increase negative affectivity and disrupt the ability to regulate emotion with respect to current situations and goals. Attention bias toward negative information may prolong a negative emotional state, reduce tolerance to unpleasant feelings, and thus increase the chance to avoid an aversive situation in the future. Additionally, attention bias can tax cognitive resources that are otherwise utilized to orchestrate how to modulate the experience and expression of emotion with adaptive emotion regulation strategies. Although we have discussed a possible link between impaired attentional control and emotion dysregulation, few research to date has attempted to explicate their causal relationship. We recommend a future study that examines how a specific type of attention affects various stages of emotion regulation process.

8.4. Rhythmic Sampling of Visual Attention

One aim of the current study is to demonstrate and examine behavioral and neural oscillatory activity. There is evidence that neuronal synchrony in certain frequencies (e.g. Alpha and Gamma) have a direct bearing on single-cell firing rates, local field potentials (LFPs), and long-range communications between brain areas that are modulated by attention (Bonnefond et al., 2017; Busch, Dubois, & VanRullen, 2009; Buschman & Miller, 2009; Dugué, Marque, & VanRullen, 2011; Gray, 1994). If oscillatory brain activity carries such functional meaning, it is plausible that the time-course of behavioral performance simulates rhythmic activity in the brain. The evoked power analysis presents support that behavioral performance oscillate in Theta and Alpha cycles, which is consistent with previous research (Fiebelkorn, Saalmann, et al., 2013; Landau & Fries, 2012; Song et al., 2014).

Despite these results, we suggest exercising considerable caution to interpret our findings, and it is also worth discussing limitations of the current study and recommendations for future directions. First, future research needs to address the inter-individual variability in peak frequency of behavioral oscillations. Prior research sought to identify a uniform frequency in oscillatory behavioral activity such as 7 or 10 Hz (VanRullen, 2016). However, when we examined the frequency-domain plots of each individual, we noticed that individual peak frequencies varied considerably from person to person. This leads to the question whether there exist significant individual difference in peak frequency that is associated with measurable behavioral outcomes. Recently Samaha and Postle (2015) administered a two-flash fusion task where participants were asked to report whether they perceived two successively presented flashes as a single flash or two discrete flashes. The authors found that individuals with higher occipital Alpha frequencies corresponded to finer temporal resolution of perception evidenced by lower two-flash threshold compared with those with lower Alpha frequencies. The results suggest that individuals with high Alpha frequency can sample visual information at rapid cycles, and as a result, they are better able to discriminate subtle changes in the environment. Although this small group study needs replication, our non-significant finding in the induced power analysis can be attributed to such individual difference in temporal resolution of perception, which can vary depending on task characteristic, sensory modality, and other individual parameters.

Second, it is worth discussing two important methodological issues regarding experimental design. The following discussion concerns how to obtain valid and reliable temporal estimates of behavioral performance. The first issue is whether the time course of mean discrimination accuracy and reaction time in our study accurately represented the true trajectory of behavioral oscillations. Our response option was two-alternative forcedchoice, and we surmise that a significant number of correct responses may represent correctly guessed responses. Depending on the ratio of “true” correct responses and correctly guessed responses, corresponding measurement error must have been added to the mean time course of behavioral performance. To address this problem, our recommendation is to obtain confidence ratings from participants. Although participant’s self-report may not be as reliable as objective measures such as behavioral data, including trials with only high confidence ratings may increase the validity of obtained measurements. The second issue is how many intervals of SOA’s and how many trials per SOA are needed. The sampling rate of Experiment 1 and Experiment 2 was set to 84.7 Hz with the shortest time interval between SOA’s being 11.8 ms, which provided a fine-grained temporal window into behavioral outcomes. However, this experimental setup significantly reduced the number of trials per SOA. After excluding trails with reactions times of greater than 2 seconds and trials with incorrect responses in reaction time, the mean trial count per SOA was about 6, but we acknowledged that the means averaged across such small number of trials could potentially be biased estimates. To increase the reliability of time course data, we chose to apply a moving window. Unless the focus of investigation is on high frequency behavioral oscillations, it would be better to reduce sampling rate (40-60 Hz) and collect data from each participant over multiple sessions.

Third, the present study corraborates that endogenous and exogenous attention operates on discrete and independent mechanisms. In our evoked power analysis, both Theta and Alpha frequencies are lower for the endogenous attention task compared with the exogenous attention task. Previous research demonstrated that exogenous attention is engaged faster (50 ms after cue onset) than endogenous attention (300 ms after cue onset; Berger, Henik, & Rafal, 2005). In addition, saliency-driven attention often requires faster reaction time such as when one hits the break when a car abruptly cuts in front whereas voluntary endogenous attention allows more time to initiate a calculated and goal-directed behavior. Based on research on cross-frequency coupling by Bonnefond et al. (2017), Gamma oscillations nested within alpha oscillations are responsible for encoding information into Alpha cycles. We surmise that lower Alpha rhythm may enable the transfer of a greater amount of information per Alpha cycle compared with higher Alpha rhythm, but at the cost of reduced sampling rates and thus lower temporal resolution. Future research can address the question by sampling people whose behavioral performance oscillates at varying Alpha frequencies and examining the relationship between the peak Alpha frequency and behavioral outcomes.

Fourth, behavioral oscillations may be modulated by task difficulty. Our review of existing studies on behavioral oscillations revealed that studies using detection or discrimination accuracy as behavioral outcome set task difficulty (e.g. luminance of the target) to the threshold level and the oscillatory effects were relatively small (VanRullen, 2016). Since we found that overall accuracy was considerably higher above the chance level (85 and 82% in Experiment 1 and Experiment 2, respectively), behavioral oscillations may have manifested weakly in our experiments. In other words, one may find behavioral performance relatively level across time with random jitters when target stimuli are presented either outside the perceptual range or at the supra-threshold level. In future research, time-course of behavioral performance needs to be examined with varying task difficulty.

The last direction for future research concerns number of possible target locations. While existing studies had two possible target locations, we presented the target in one of the quadrants. If attention alternately samples both attended and unattended possible target locations, the number of possible target locations may affect sampling frequency. In other words, if the number of target locations increases, reduction in sampling frequency is expected. Holcombe and Chen (2013) investigated the issue in a multiple object tracking paradigm and demonstrated that as the number of targets increased the temporal frequency limit decreased from 7 Hz (one target) to 4 Hz (two targets) and 2.6 Hz (three targets). Such methodological difference may explain why the significant peak frequencies in our study (5.2 Hz and 9.1 Hz) are lower than more commonly reported frequencies of 7 and 10 Hz (VanRullen, 2016).

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Table 1

Demographic Characteristics and Meditation Experience of Study Participants (N = 113)

		Experiement 1 (*n* = 44)	Experiment 2 (*n* = 42)	Experiment 3 (*n* = 27)	Total (*N* = 113)
Sex	Male	8 (18.2%)	12 (28.6%)	8 (29.6%)	28 (24.8%)
	Female	36 (81.8%)	30 (71.4%)	19 (70.4%)	85 (75.2%)
Age		22.18 (*SD* =3.04)	21.90 (*SD* = 3.08)	22.44 (*SD* = 3.88)	22.14 (*SD* = 3.26)
Ethnicity	Caucasian	26 (59.1%)	24 (57.1%)	13 (48.1%)	63 (55.8%)
	African American	1 (2.3%)	2 (4.8%)	2 (7.4%)	5 (4.4%)
	Hispanic	8 (18.2%)	11 (26.2%)	7 (25.9%)	26 (23.0%)
	Asian American	6 (13.6)	2 (4.8%)	3 (11.1%)	11 (9.7%)
	Native American or Pacific Islander	2 (4.6%)	1 (2.4%)	0 (0 %)	3 (2.7%)
	Mixed or other	1 (2.3%)	2 (4.8%)	2 (7.4%)	5 (4.4%)
Meditation Experience	Yes	16 (36.4%)	19 (45.2%)	11 (40.7%)	46 (43.4%)
	No	28 (63.6%)	23 (54.8%)	16 59.3%	67 (59.3%)

Table 2

Summary of Pearson Correlations, Means, and Standard Deviations of Study Variables

	1	2	3	4	5	6	7	*M*	*SD*
Experiment1 (*N* = 44)									
1. Discrimination Accuracy (%)	____							85.41	8.60
2. Reaction Time (ms)	-.10	____						677.3	123.9
3. Observe	.12	-.32*	____					26.70	5.79
4. Describe	.17	-.17	.46**	____				28.89	5.16
5. Act Awareness	-.08	.04	.09	.29	____			26.32	4.89
6. Non-judge	-.08	.10	-.09	.18	.32*	____		26.57	5.70
7. Non-react	.19	-.03	.31*	.47**	.13	.05	____	21.91	3.55
8. MAAS	.10	-.03	.14	.25	.71***	.36*	.04	56.95	9.89
Experiment2 (*N* = 42)									
1. Discrimination Accuracy (%)	____							83.59	8.20
2. Reaction Time (ms)	.03	____						707.2	136.5
3. Observe	-.08	.47**	____					25.79	5.71
4. Describe	-.08	.30	.53***	____				26.79	5.82
5. Act Awareness	.08	.05	.08	.25	____			25.81	5.09
6. Non-judge	.09	.01	-.14	.36*	.45**	____		26.36	6.38
7. Non-react	-.33*	.16	.42**	.44**	.16	-.01	____	21.00	4.78
8. MAAS	.03	.27	.19	.27	.56***	.50**	.26	54.36	11.65

Note. Observe, Describe, Act Awareness, Non-judge, and Non-react are the five subscales of the Five Facet Mindfulness Questionnaire (FFMQ). MAAS = Mindfulness Attention Awareness Scale. *$p < .05$, **$p < .01$, ***$p < .001$.

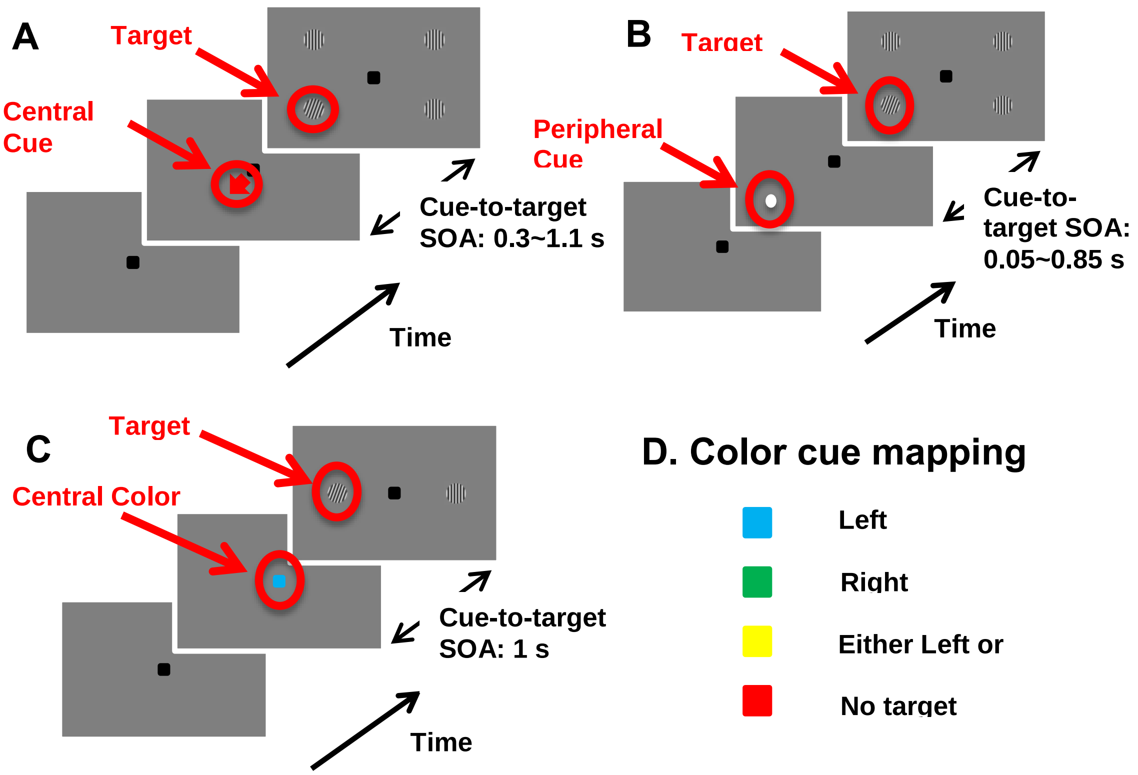


Figure 1. Schematic diagrams of Experiment1 (A), Experiment2 (B), and Experiment3 (C). (D) Color cues indicate the target location of Experiment3.

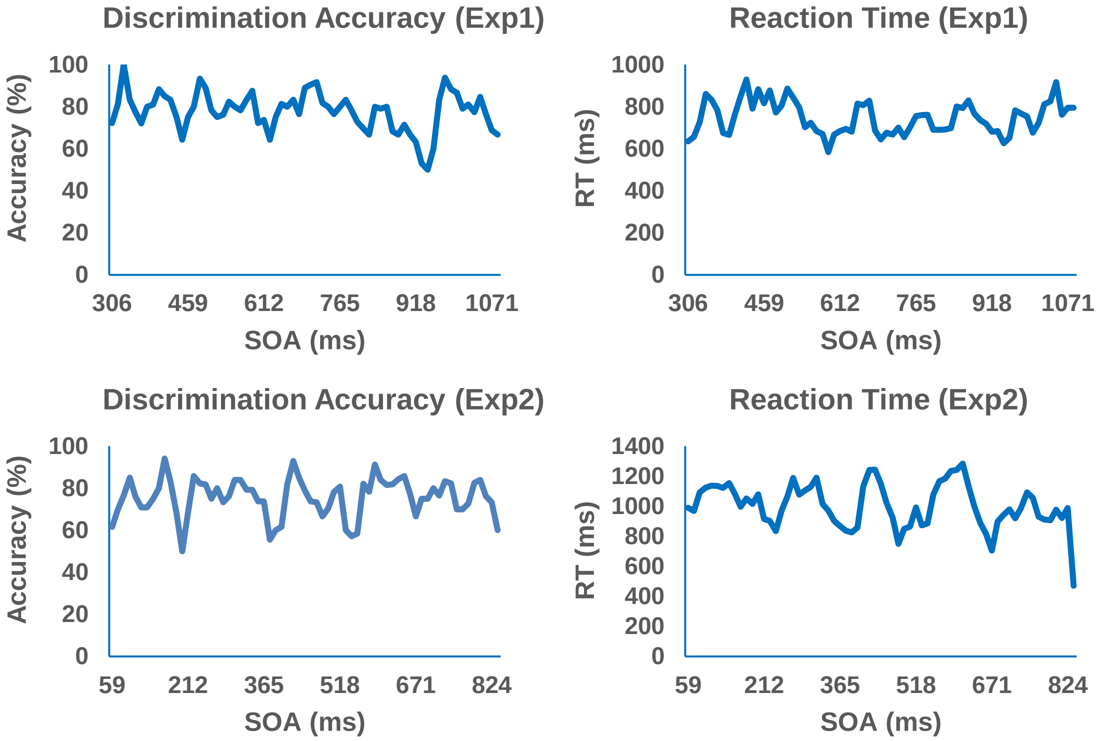


Figure 2. Examples of time course effects of discrimination accuracy and reaction time in Experiment1 (top) and Experiment2 (bottom) (selected from individual subject data). SOA = stimulus onset asynchrony.

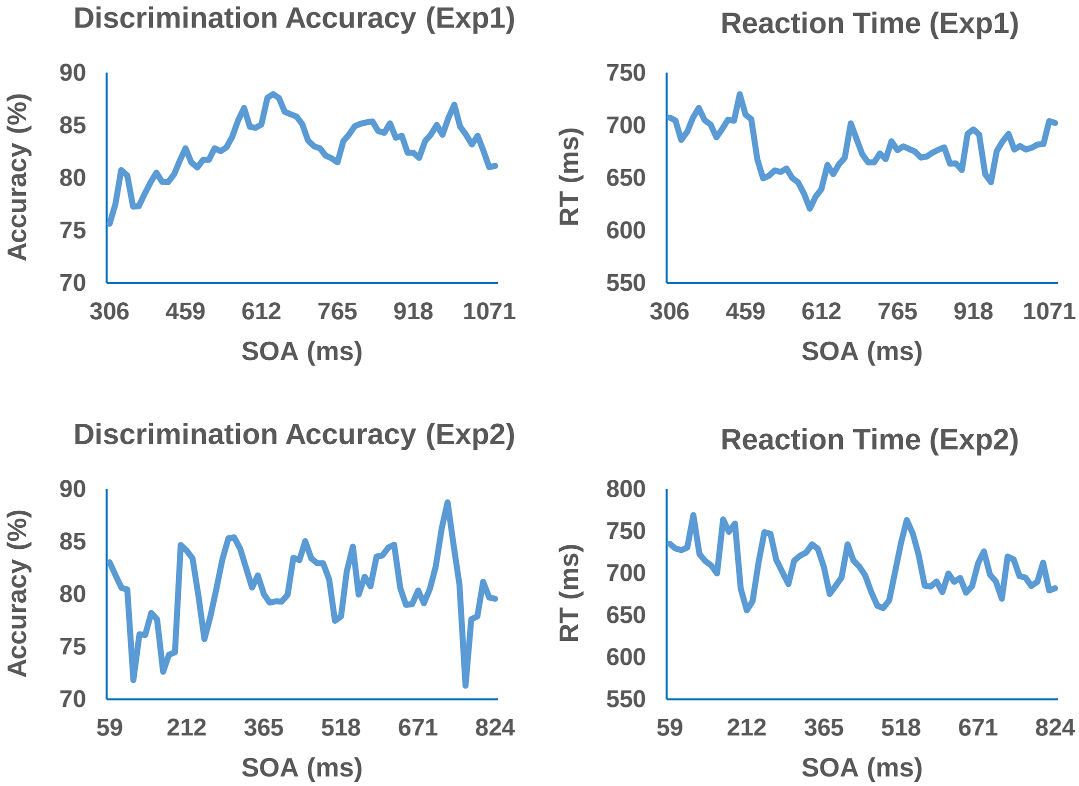


Figure 3. Mean time course of discrimination accuracy and reaction time averaged across participants in Experiment1 (top) and Experiment2 (bottom). SOA = stimulus onset asynchrony.

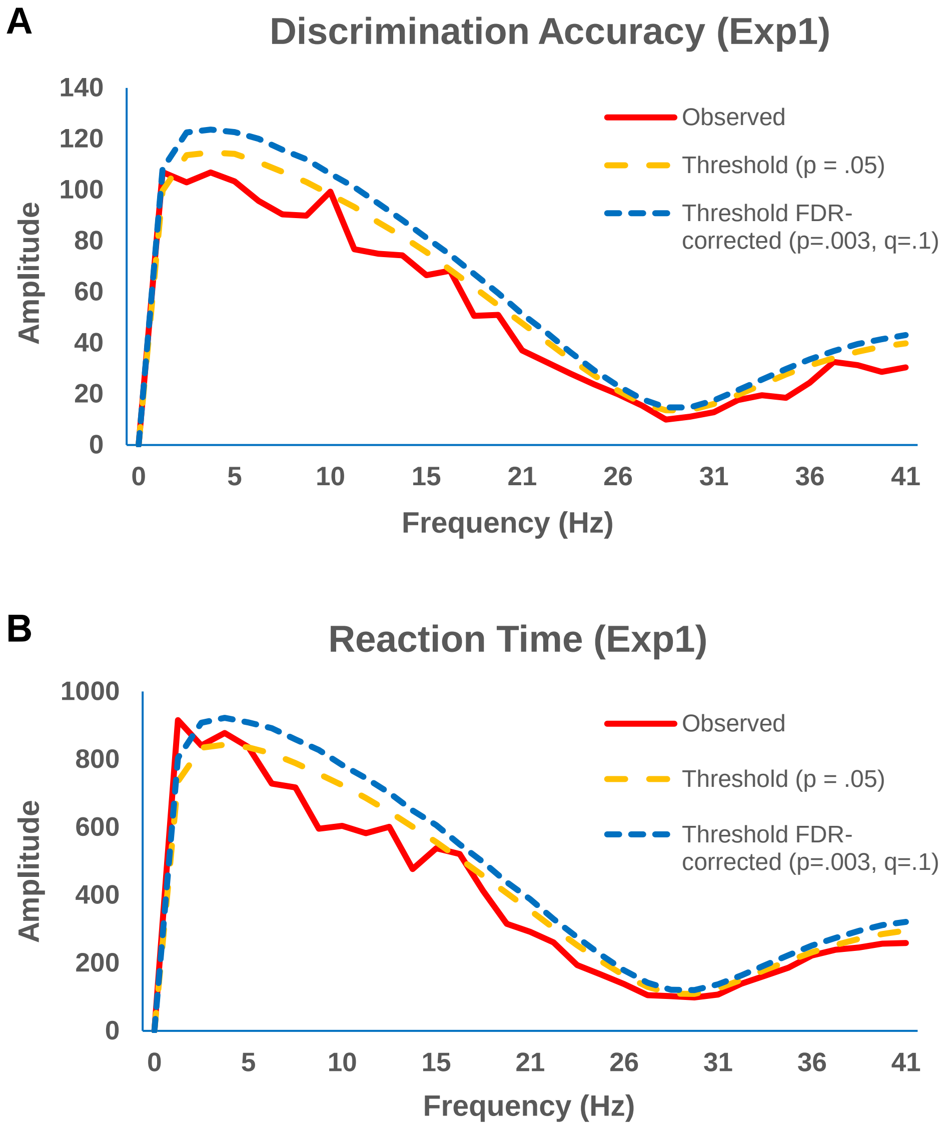


Figure 4. Induced power spectral analysis of discrimination accuracy (A) and reaction time (B) in Experiment1. Solid red line represents observed amplitude values. Orange dashed line represents uncorrected threshold (p = .05). Blue dashed line represents FDR-corrected threshold (p = .003, q = .1).

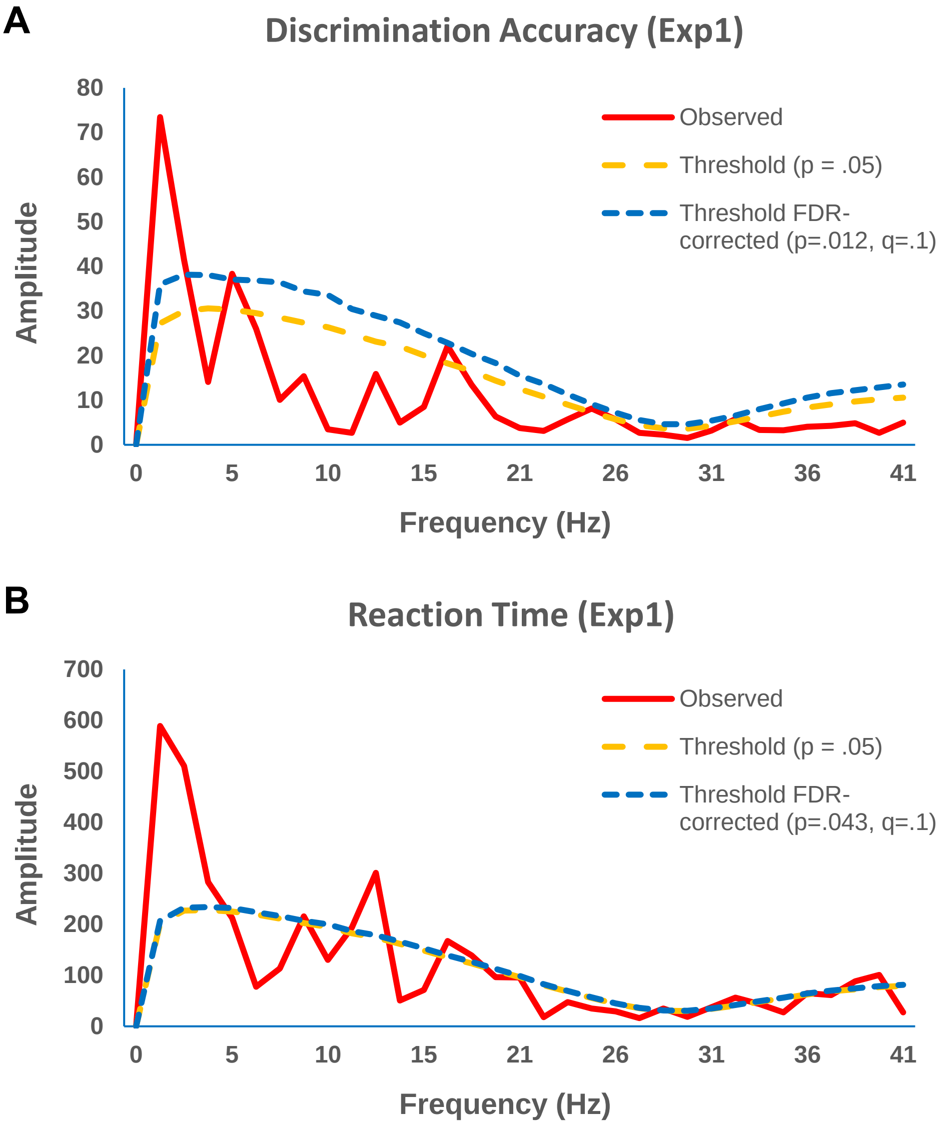


Figure 5. Evoked power spectral analysis of discrimination accuracy (A) and reaction time (B) in Experiment1. Solid red line represents observed amplitude values. Orange dashed line represents uncorrected threshold (p = .05). Blue dashed line represents FDR-corrected threshold (p = .012 for discrimination accuracy and p=.043 for RT, q = .1).

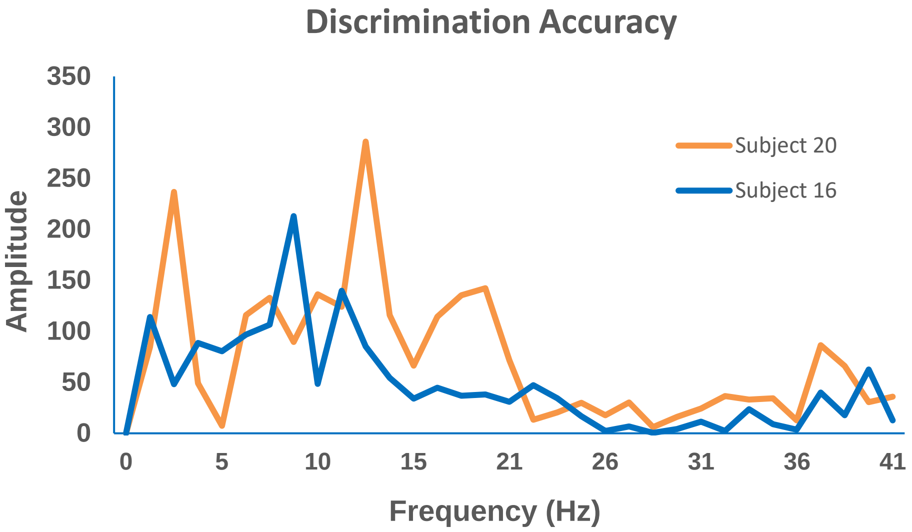


Figure 6. Power spectra of discrimination accuracy in Experiment 1 for two individual subjects.

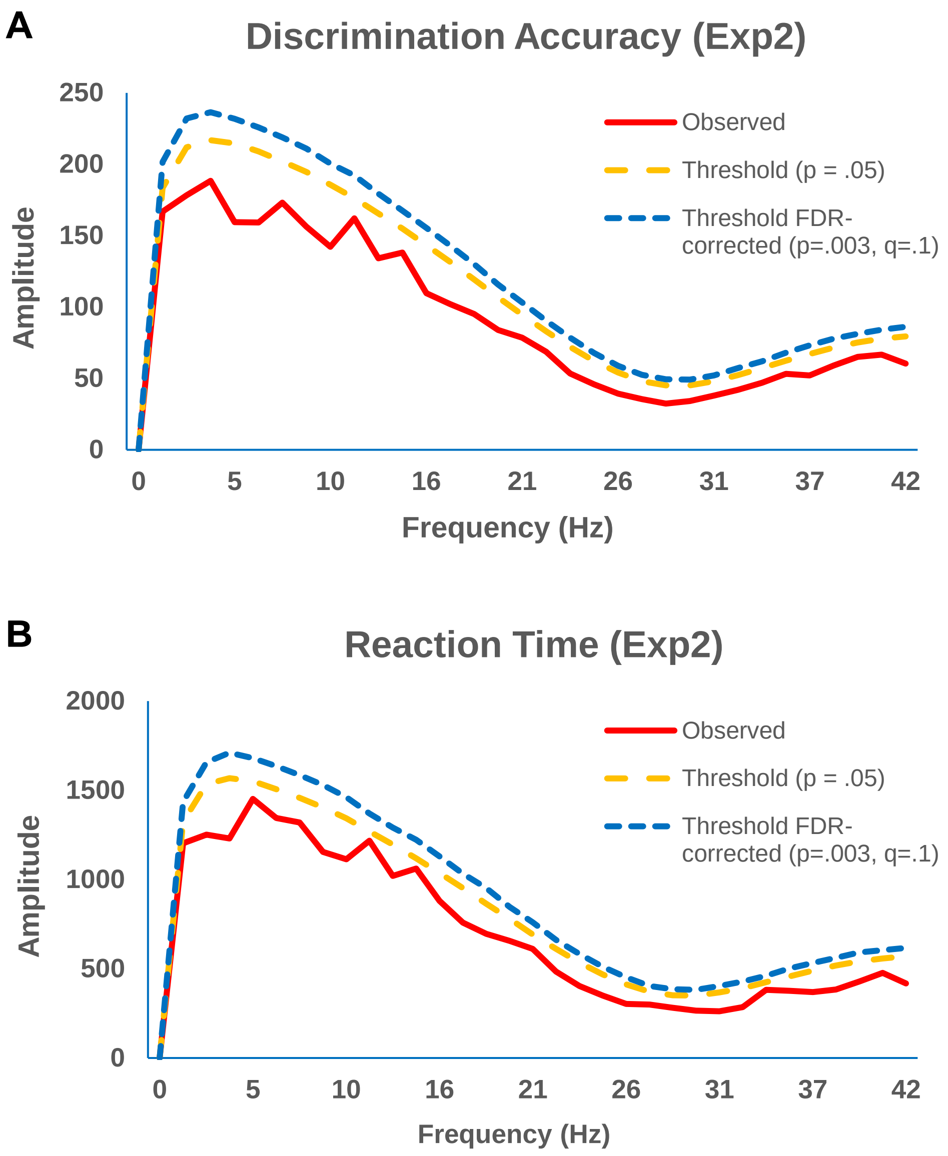


Figure 7. Induced power spectral analysis of discrimination accuracy (A) and reaction time (B) in Experiment2. Solid red line represents observed amplitude values. Orange dashed line represents uncorrected threshold (p = .05). Blue dashed line represents FDR-corrected threshold (p = .003, q = .1).

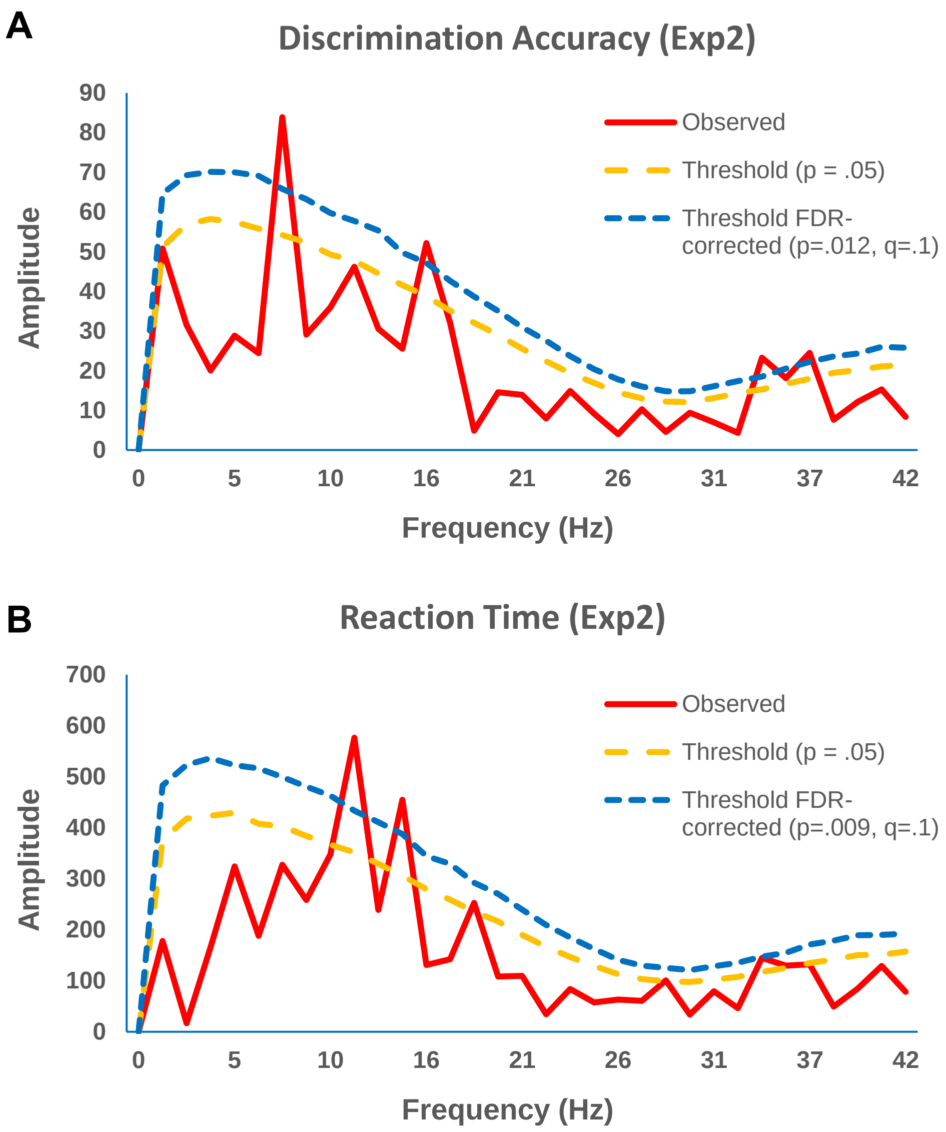


Figure 8. Evoked power spectral analysis of discrimination accuracy (A) and reaction time (B) in Experiment2. Solid red line represents observed amplitude values. Orange dashed line represents uncorrected threshold (p = .05). Blue dashed line represents FDR-corrected threshold (p = .012 for discrimination accuracy and p=.009 for RT, q = .1).

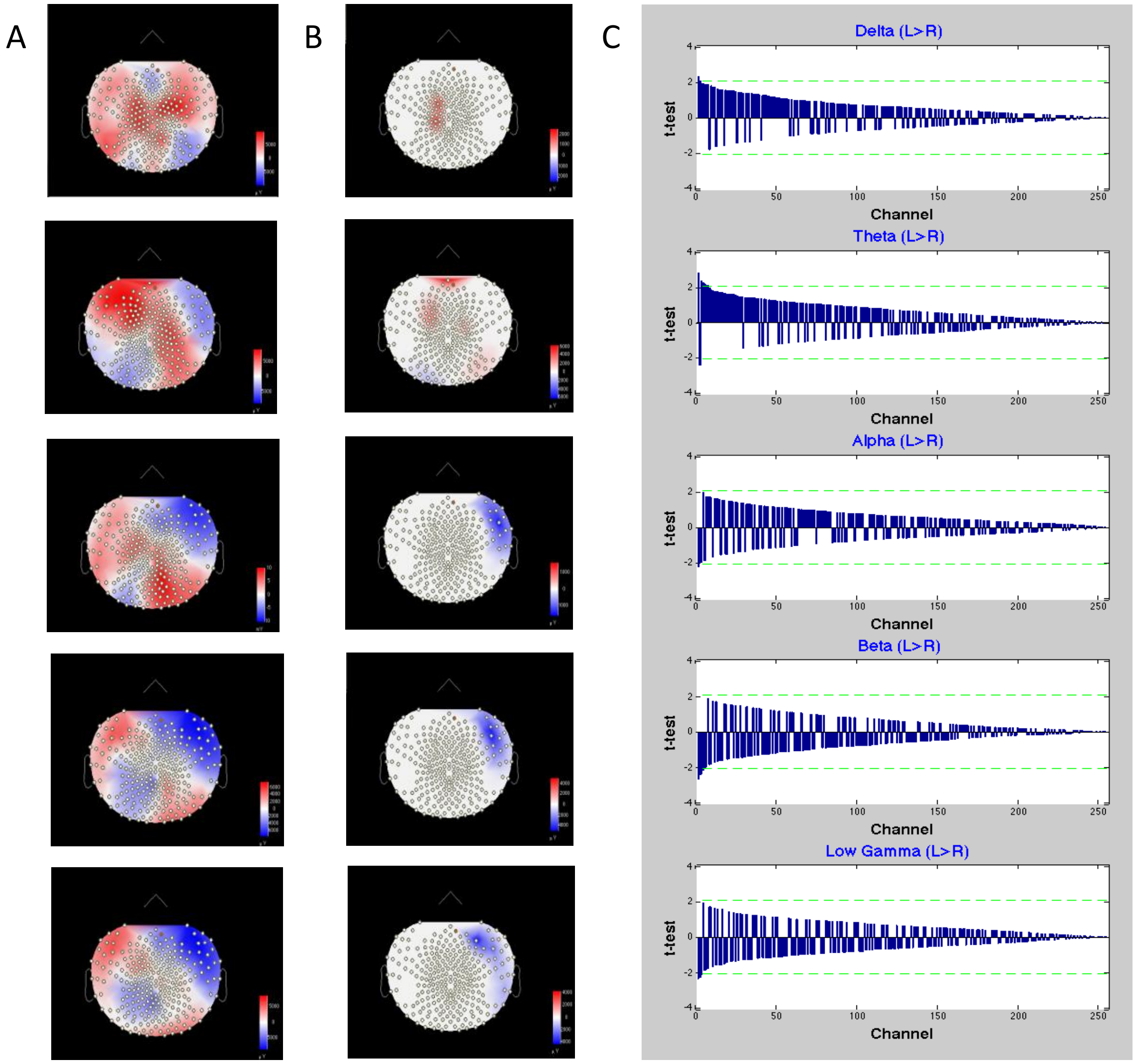


Figure 9. Frequency analysis results of the cue-to-the left condition relative to the cue-to-the right condition (Induced). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*’s <.05 (B). Positive values (red) mean higher index values for the ‘cue-to-the-left’ condition while negative values (blue) mean higher values for the ‘cue-to-the-right’ condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

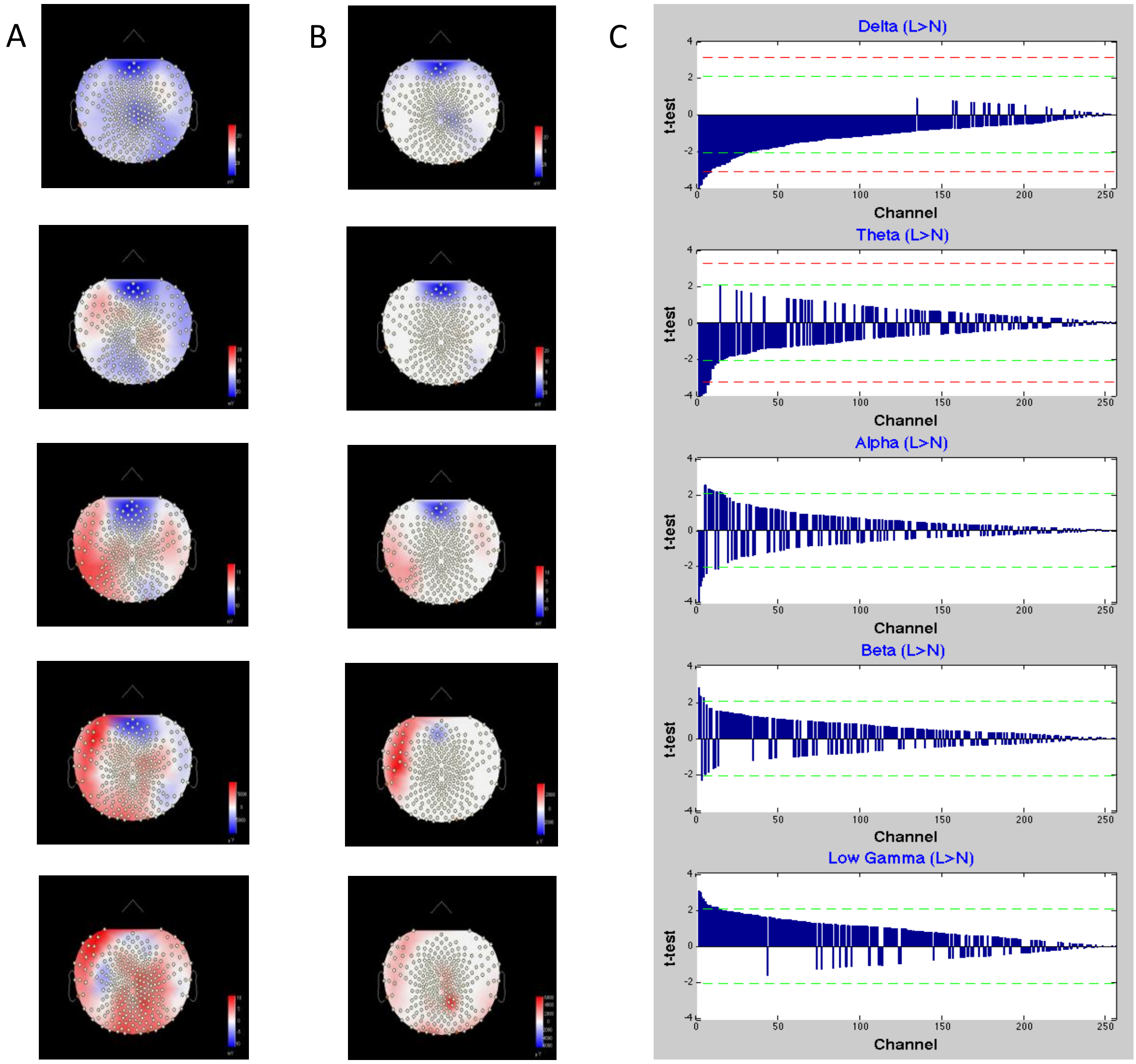


Figure 10. Frequency analysis results of the cue-to-the left condition relative to the no-target condition (Induced). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

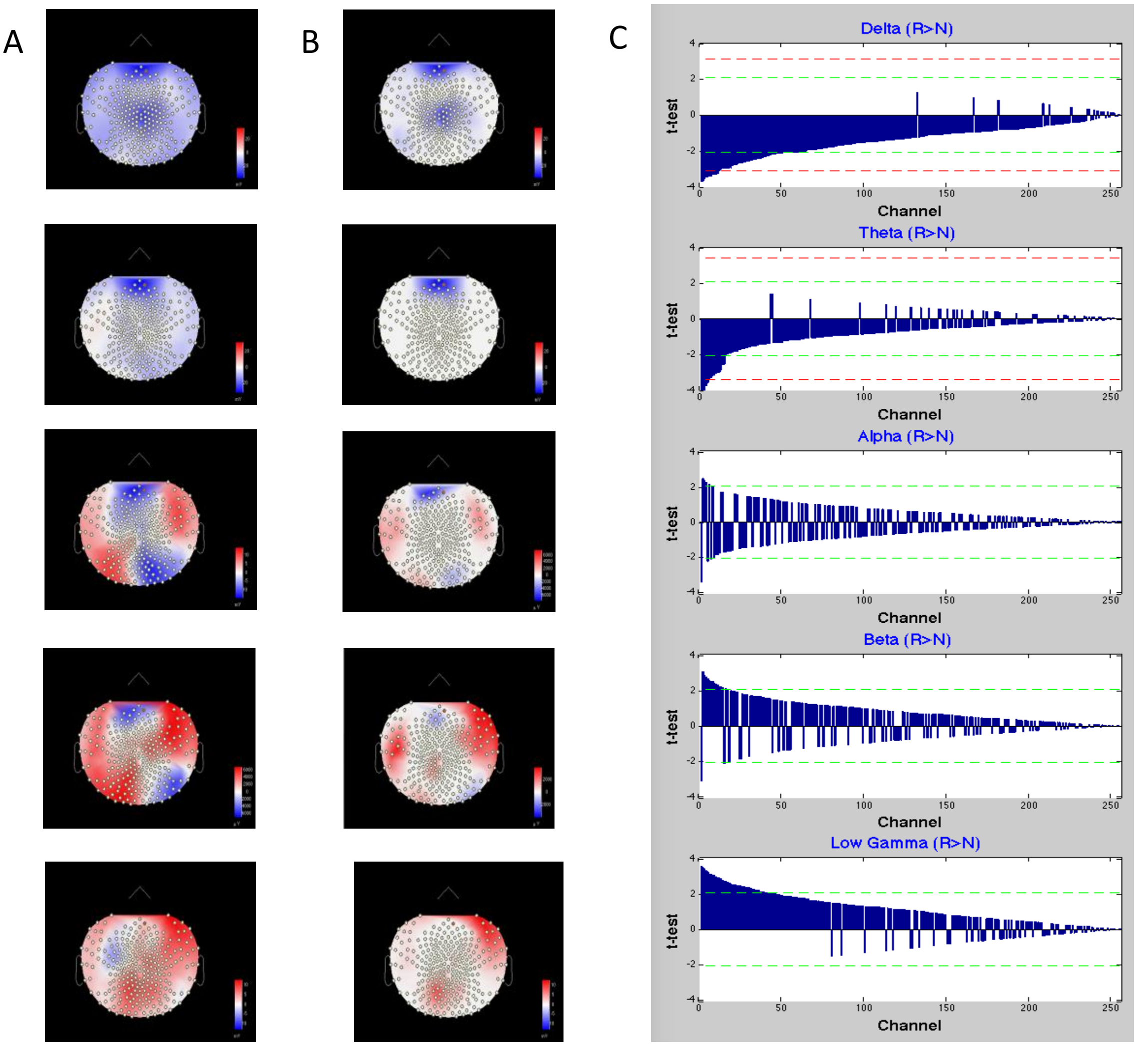


Figure 11. Frequency analysis results of the cue-to-the right condition relative to the no-target condition (Induced). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

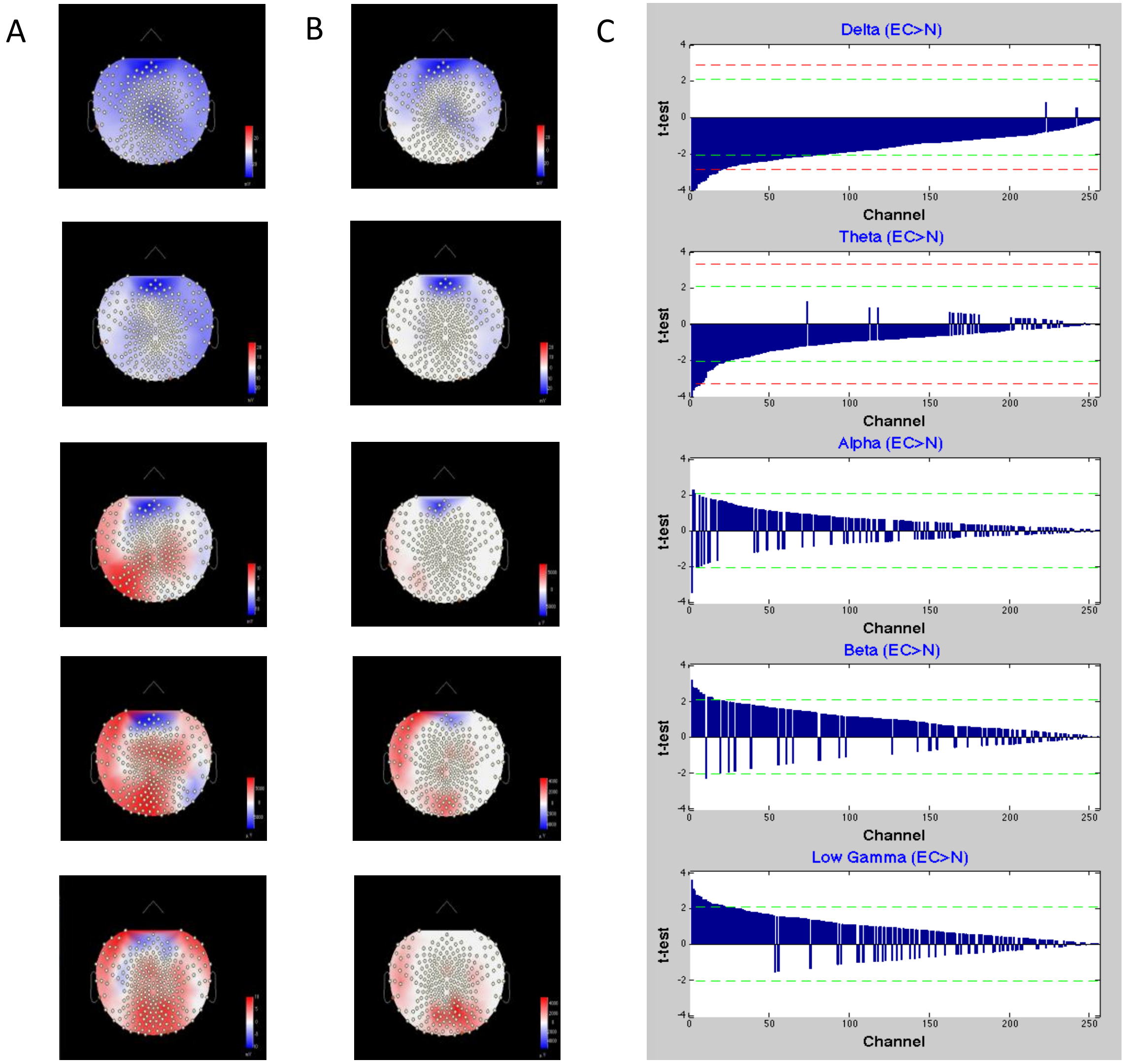


Figure 12. Frequency analysis results of the either-direction condition relative to the no-target condition (Induced). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*’s <.05 (B). Positive values (red) mean higher index values for the ‘cue-to-the-left’ condition while negative values (blue) mean higher values for the ‘cue-to-the-right’ condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

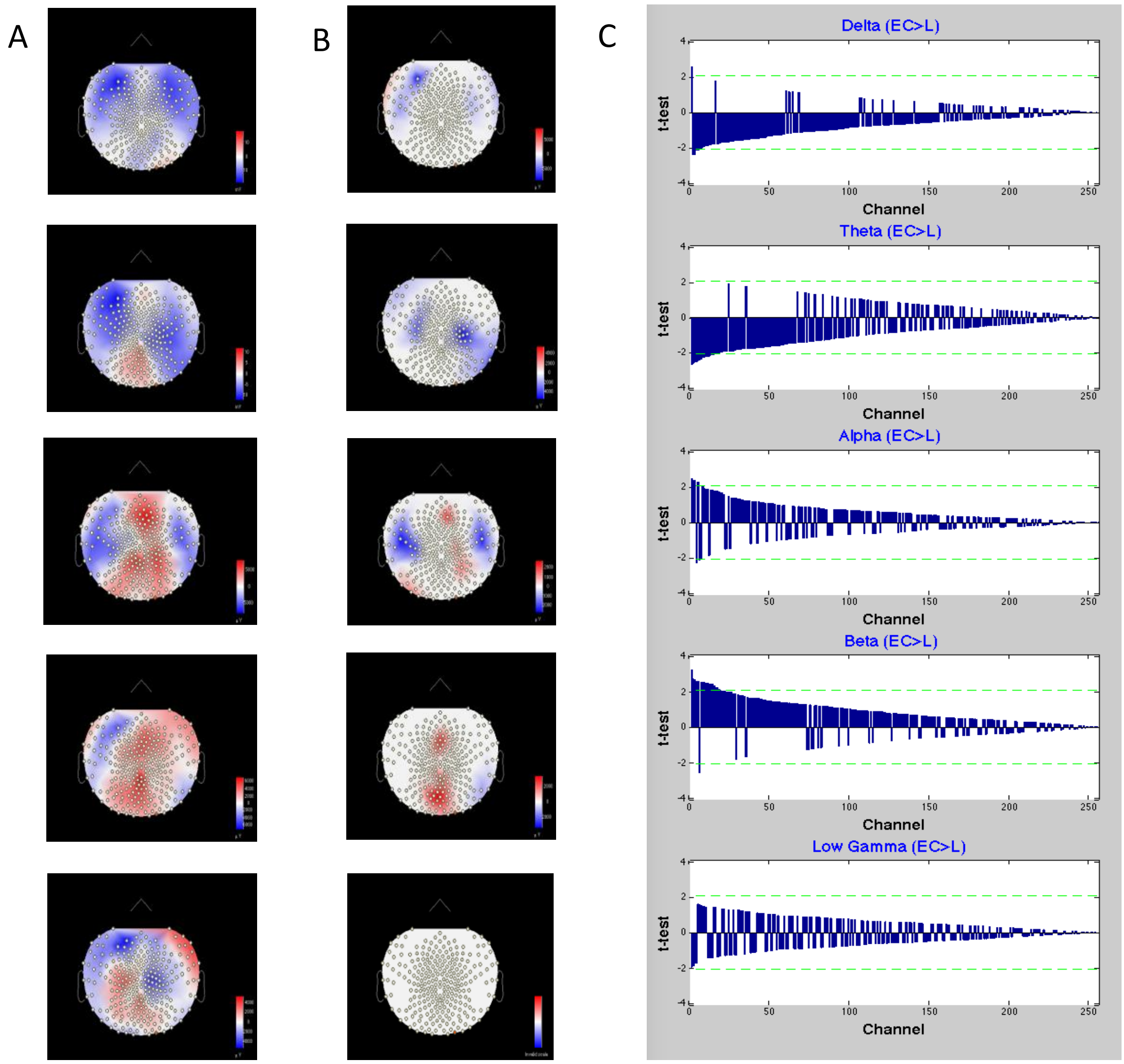


Figure 13. Frequency analysis results of the either-direction condition relative to the cue-to-the-left condition (Induced). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

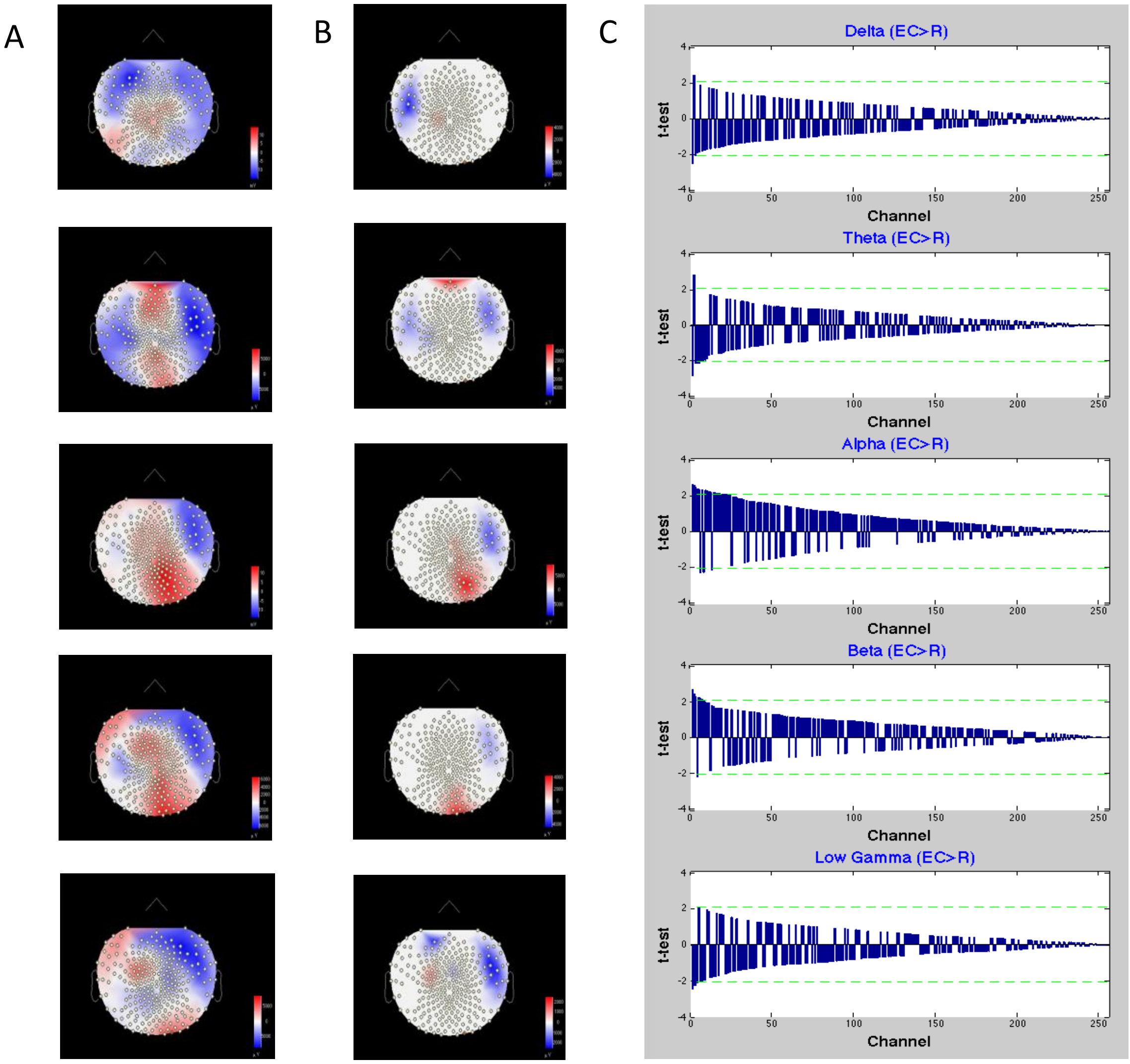


Figure 14. Frequency analysis results of the either-direction condition relative to the cue-to-the-right condition (Induced). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

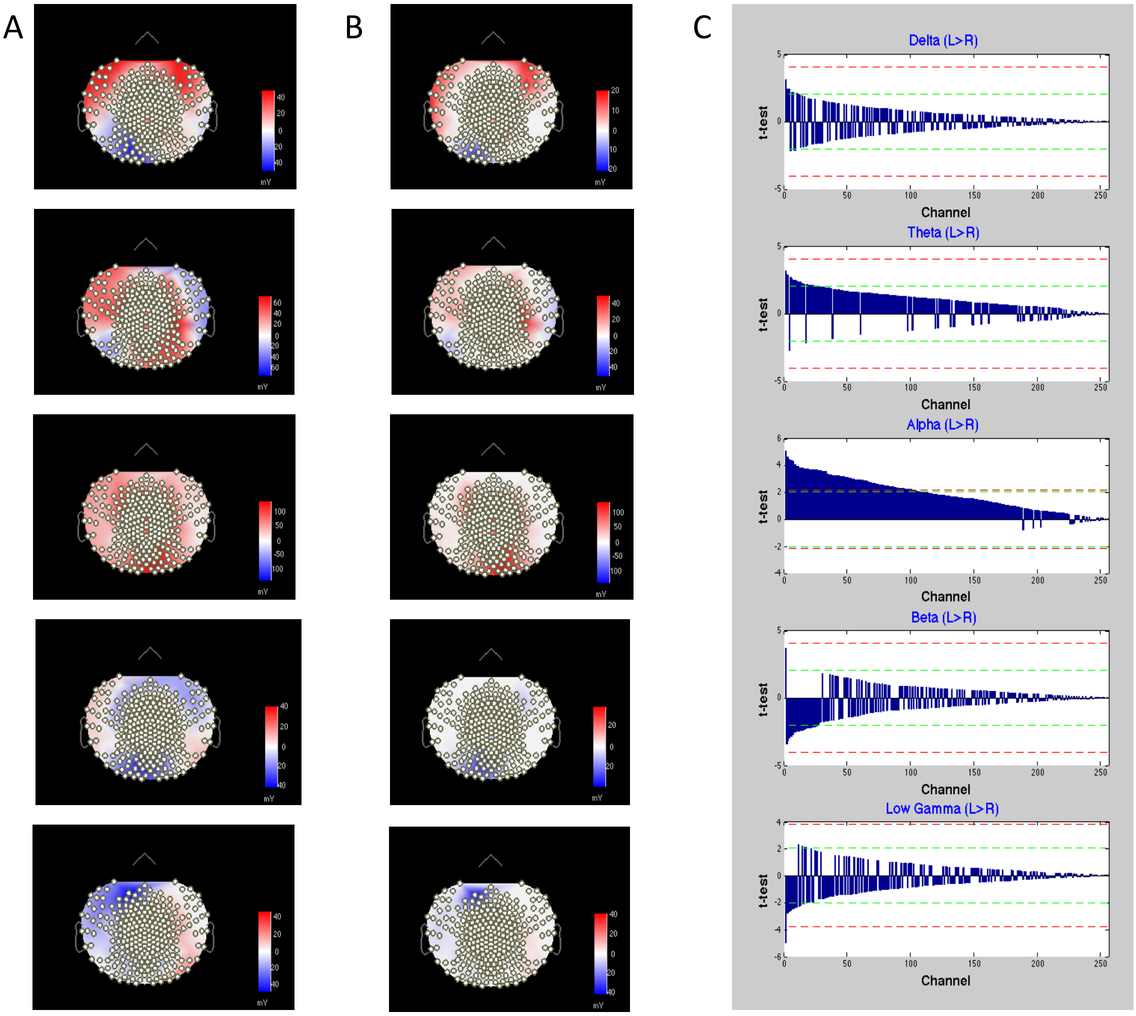


Figure 15. Frequency analysis results of the cue-to-the left condition relative to the cue-to-the right condition (Evoked). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*’s <.05 (B). Positive values (red) mean higher index values for the ‘cue-to-the-left’ condition while negative values (blue) mean higher values for the ‘cue-to-the-right’ condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

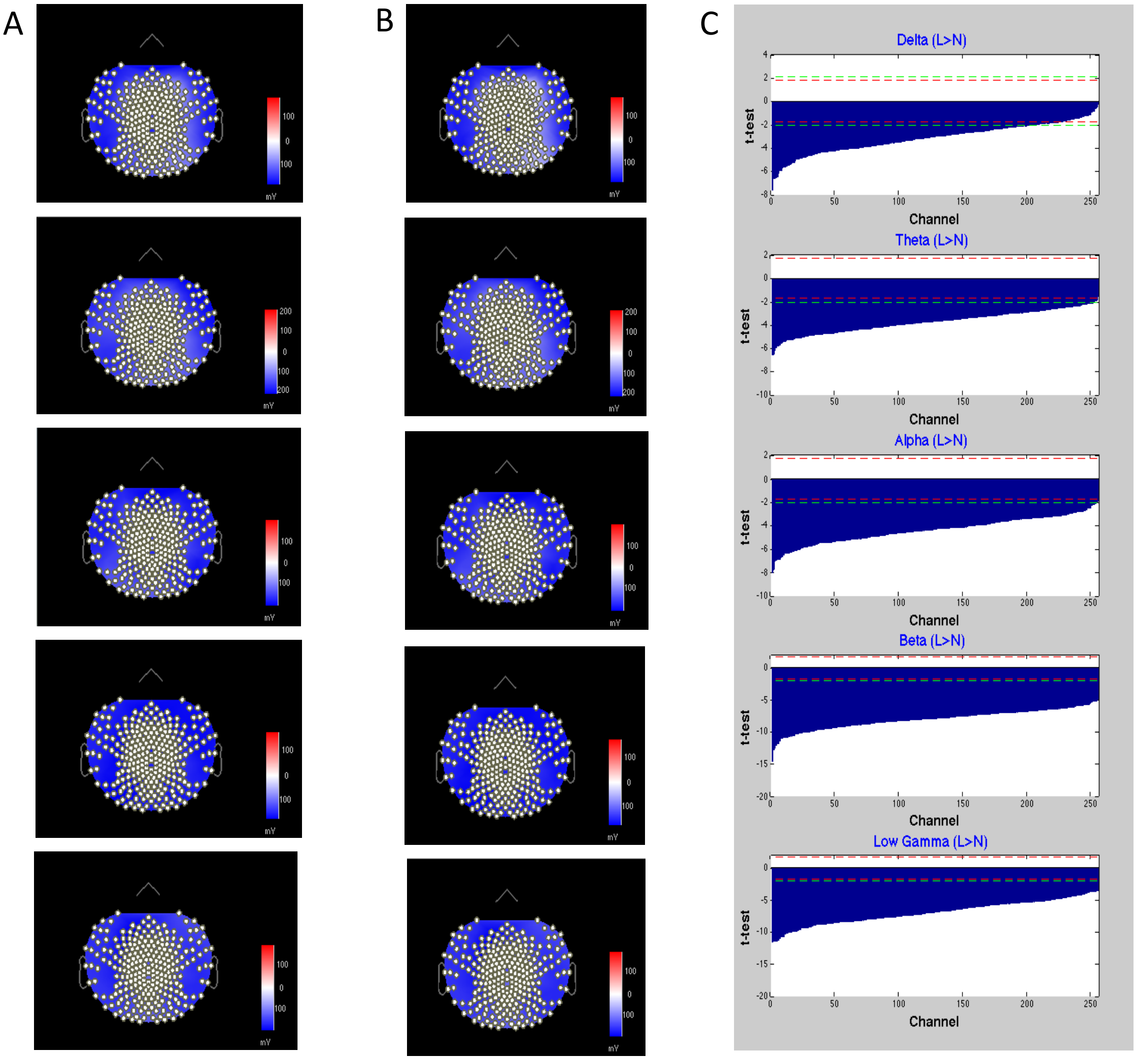


Figure 16. Frequency analysis results of the cue-to-the left condition relative to the no-target condition (Evoked). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

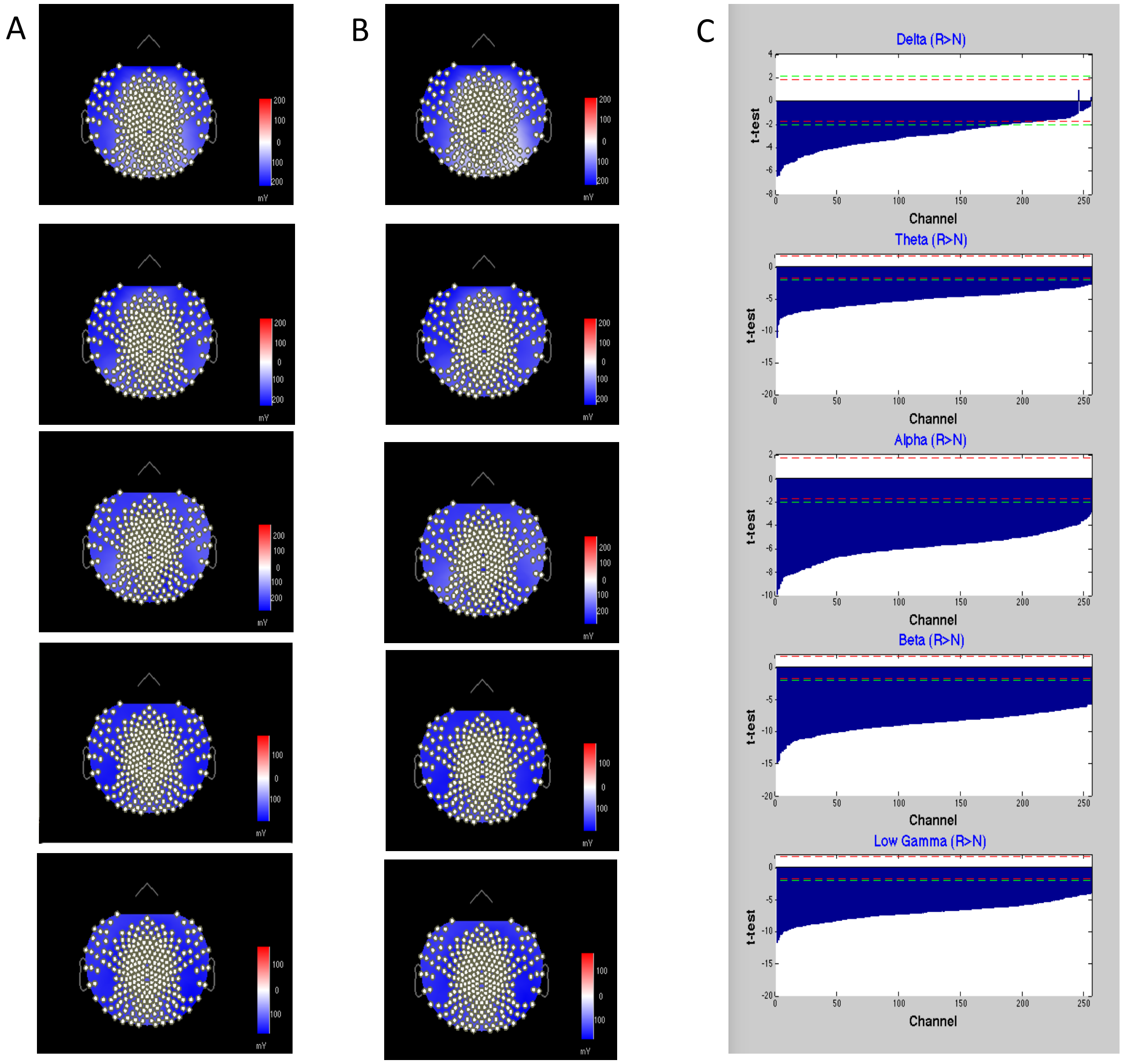


Figure 17. Frequency analysis results of the cue-to-the right condition relative to the no-target condition (Evoked). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

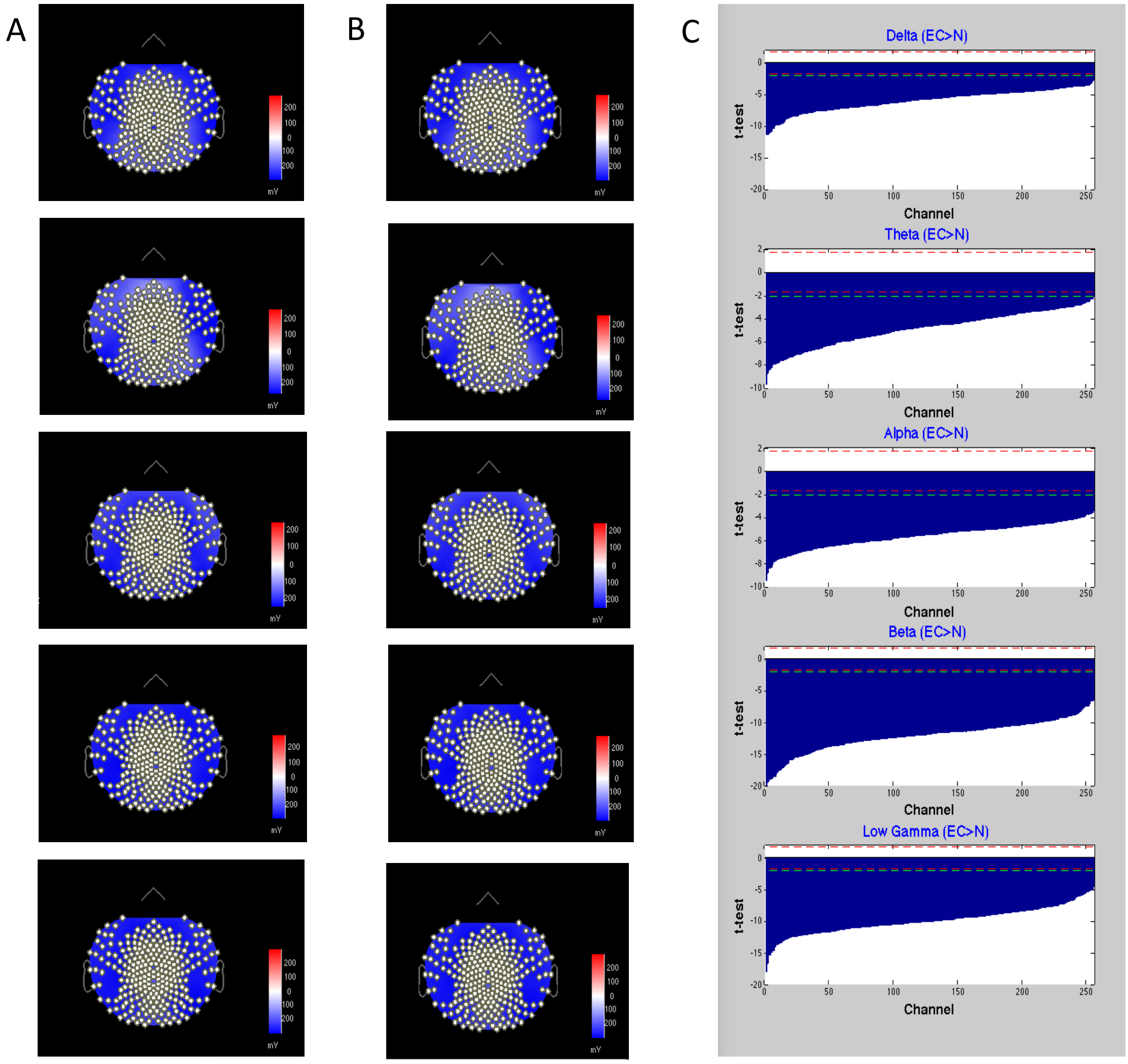


Figure 18. Frequency analysis results of the either-direction condition relative to the no-target condition (Evoked). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

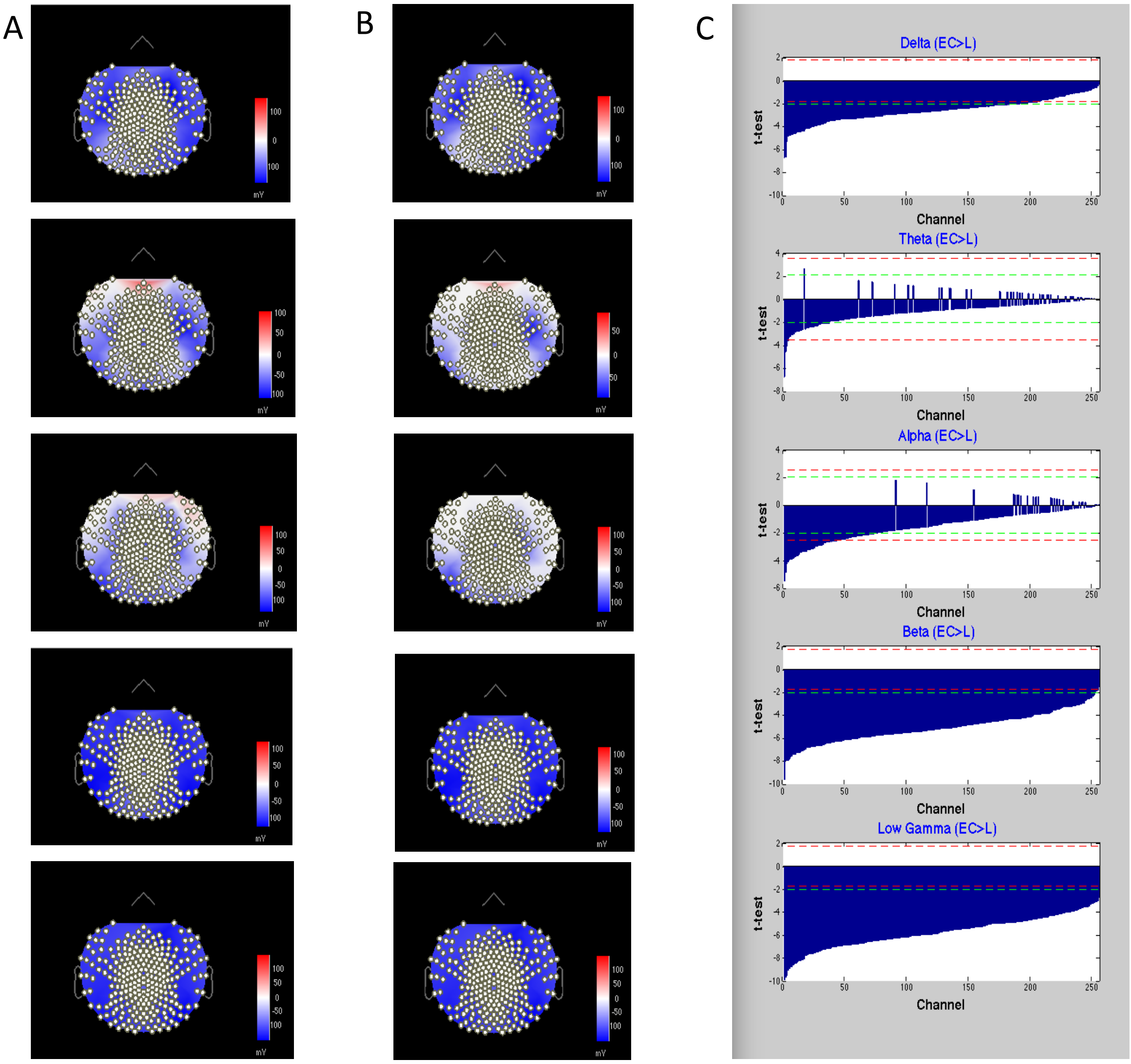


Figure 19. Frequency analysis results of the either-direction condition relative to the cue-to-the-left condition (Evoked). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.

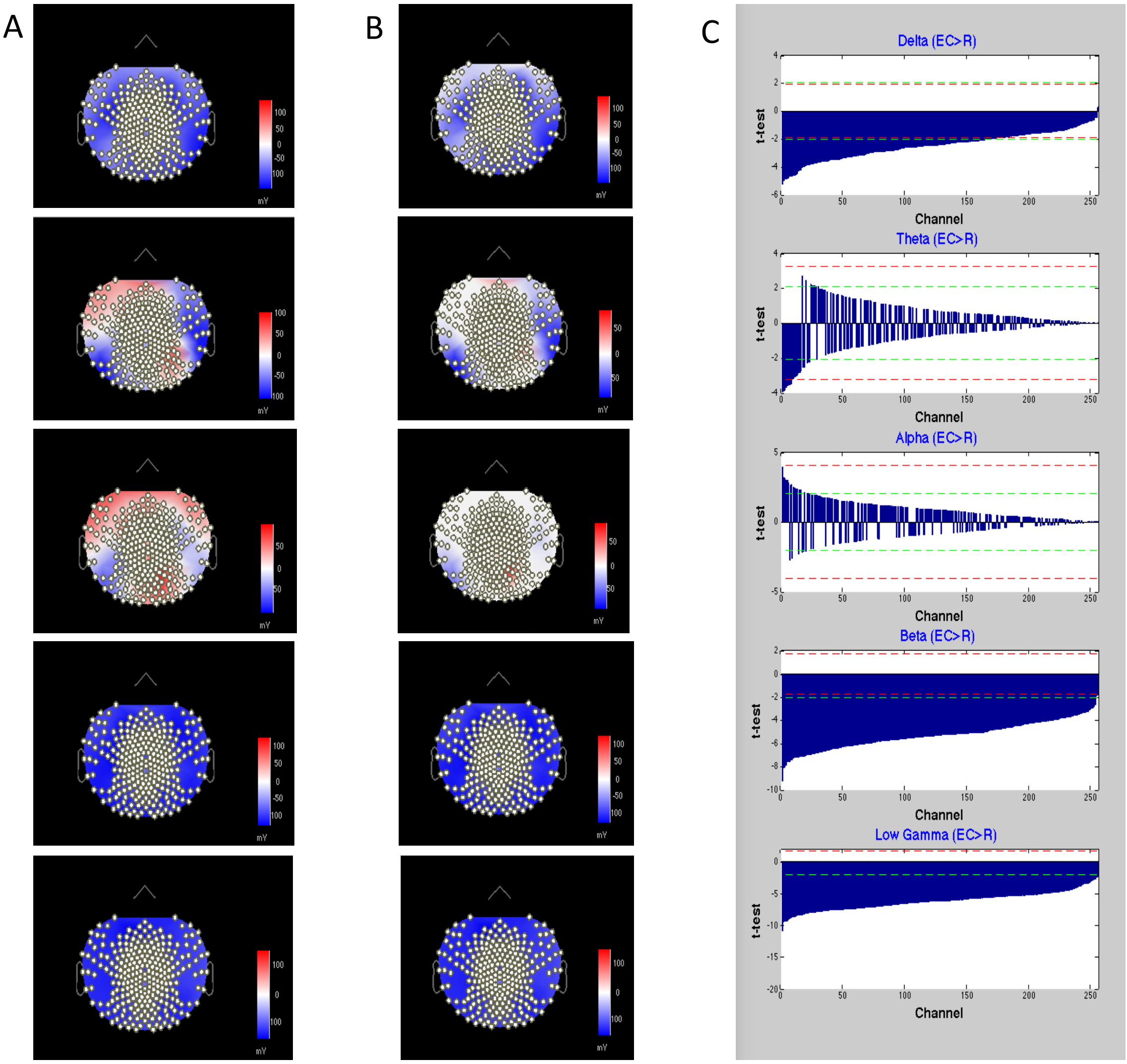
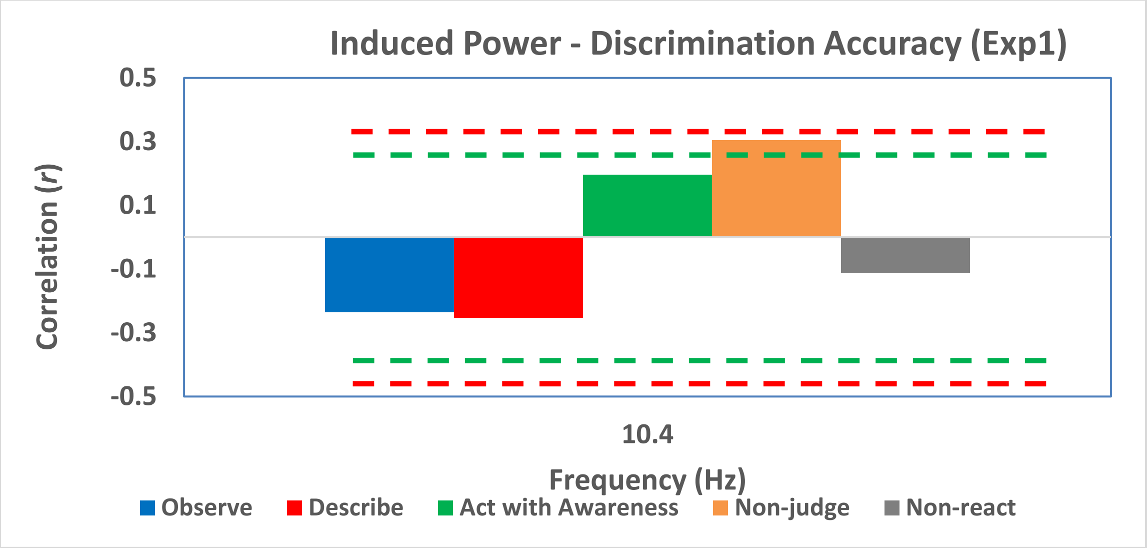


Figure 20. Frequency analysis results of the either-direction condition relative to the cue-to-the-right condition (Evoked). (A) and (B) Topographical maps represent index values from all electrodes (A) and those significant at uncorrected *p*'s <.05 (B). Positive values (red) mean higher index values for the 'cue-to-the-left' condition while negative values (blue) mean higher values for the 'cue-to-the-right' condition. (C) Blue bars represent the statistics of one-sample t-tests at 256 sensors. Green line represent the threshold equivalent to uncorrected *p*=.05 and red line represents the threshold equivalent to q=.10 after accounting for multiple comparisons.



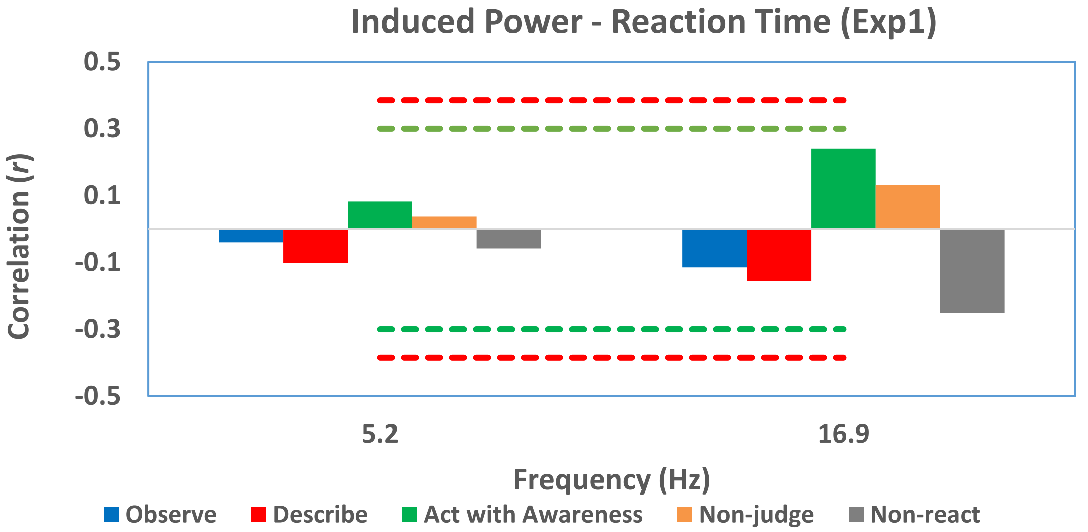


Figure 21. Correlation between induced power spectra and subscale scores of the FFMQ for discrimination accuracy in Experiment1. Bar graph shows Pearson correlation coefficients across frequencies. Green dashed line represents uncorrected threshold ($p = .05$). Red dashed line represents FDR-corrected threshold ($q = .1$, $p = .002$ for accuracy and $p = .001$ for RT).

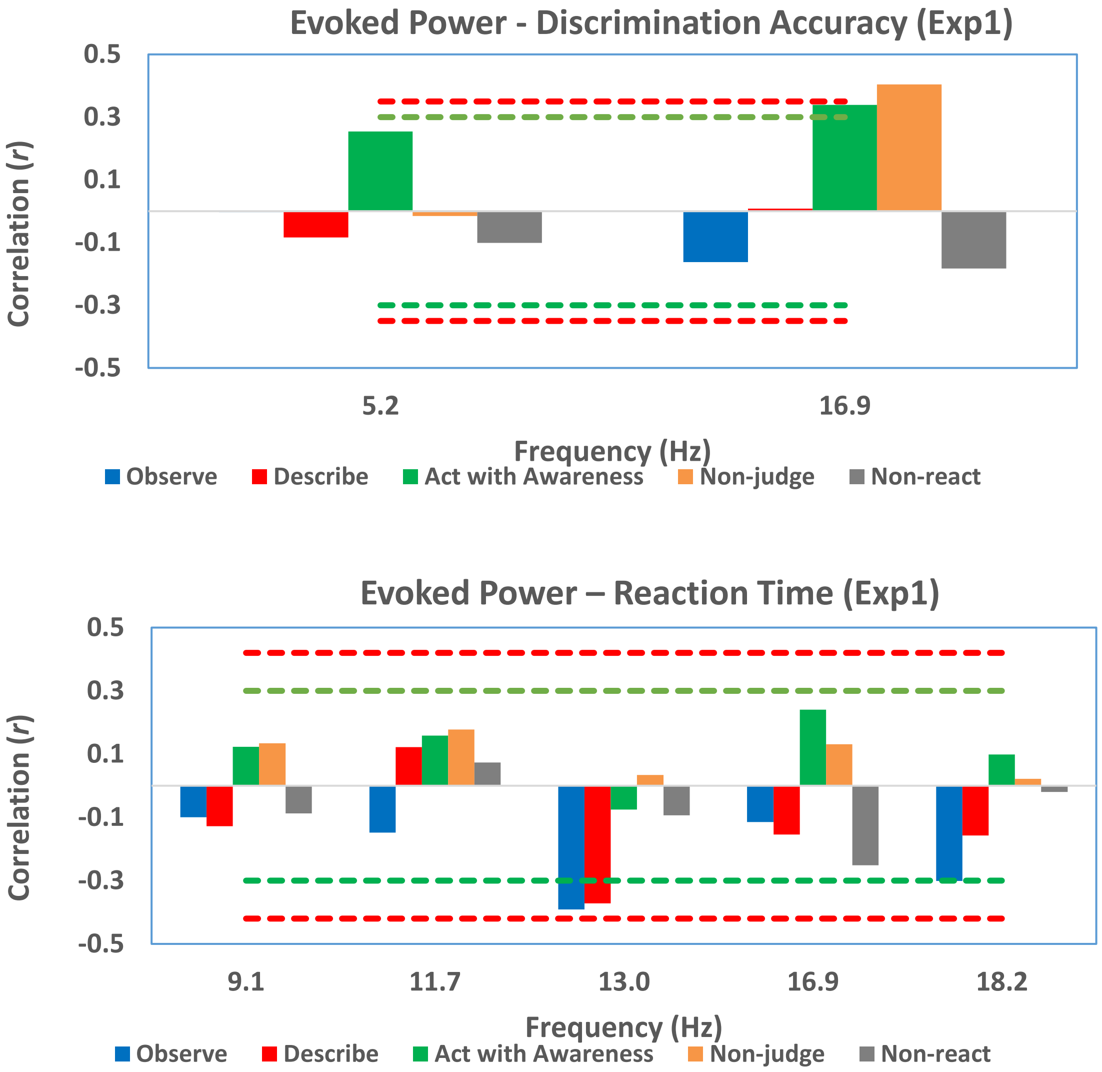


Figure 22. Correlation between evoked power spectra and subscale scores of the FFMQ for discrimination accuracy in Experiment1. Bar graph shows Pearson correlation coefficients across frequencies. Green dashed line represents uncorrected threshold (*p* = .05). Red dashed line represents FDR-corrected threshold (*q* = .1, *p* = .002 for accuracy and *p* = .004 for RT).

Figure 23. Correlation between evoked power spectra and subscale scores of the FFMQ for discrimination accuracy in Experiment2. Bar graph shows Pearson correlation coefficients across frequencies. Green dashed line represents uncorrected threshold ($p = .05$). Red dashed line represents FDR-corrected threshold ($q = .1$, $p = .001$ for accuracy and $p = .007$ for RT).