MINDFULNESS PREDICTS EFFICIENT COGNITIVE CONTROL: AN EEG STUDY OF THETA-BAND NEURAL OSCILLATIONS

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Arts in Psychology

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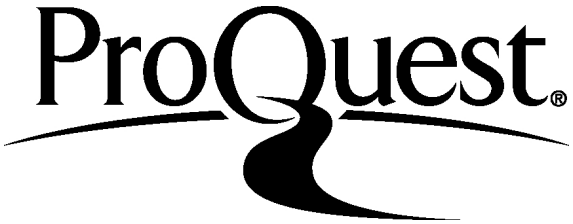

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ABSTRACT

Mindfulness is the state of nonjudgmental attention to experiences in the present moment. It is related to a number of psychological benefits, including enhanced attention and emotion regulation. Researchers have increasingly focused on the mechanisms that contribute to these benefits, which has led to numerous findings that mindfulness is related to improved cognitive control. Results from recent event-related potential studies of mindfulness indicate that mindfulness may improve cognitive control in part through enhancements in frontal midline theta – neuronal oscillations occurring between 4-8 Hz that are thought to reflect the medial prefrontal cortex signaling the need for cognitive control. The present study aimed to test whether trait mindfulness predicted stronger frontal midline theta activity during an attentionally-demanding task (the flanker task). Depression and worry were also assessed. Mindfulness and depression were both related to reduced frontal midline theta activity, but only depression was associated with poorer performance. Findings suggest that while mindfulness is related to greater efficiency of cognitive control signaling, depression is related to poorer cognitive functioning.

Chapter 1

INTRODUCTION

Mindfulness is a multifaceted construct usually described as the state of nonjudgmental attention to experiences in the present moment (Kabat-Zinn, 1990). It is believed to contribute to well-being and happiness, at least in part through disengagement from automatic thoughts, habits, and unhealthy behavior patterns (Brown & Ryan, 2003). Mindfulness is associated with enhanced attention regulation, body awareness, and emotion regulation (Hölzel, Lazar, Gard, Schuman-Olivier, Vago, & Ott, 2011). Mindfulness also positively impacts physical health through improved immune function, reduced blood pressure and cortisol levels, and increased telomerase activity (see Hölzel et al., 2011). Because of its psychological benefits, mindfulness has been incorporated into numerous mental disorder treatments, including exposure-based cognitive therapy (EBCT; Hayes, Beevers, Feldman, Laurenceau, & Perlman, 2005), acceptance and commitment therapy (ACT; Hayes, Strosahl, & Wilson, 1999), mindfulness-based cognitive therapy (MBCT; Teasdale, Segal, & Williams, 1995), dialectical behavior therapy (DBT; Linehan, 1993), and relapse prevention (RP; Marlatt & Gordon, 1985). As a result, mindfulness has been applied to the treatment of a wide variety of clinical disorders, with general success (for a review, see Baer, 2003).

1.1 Mindfulness and Cognitive Control

Investigators have increasingly focused on the mechanisms that contribute to mindfulness' psychological benefits. Along this vein, recent years have seen an

explosion of studies linking mindfulness and mindfulness meditation to improved cognitive control – complex information processing that requires the coordination of several sub-processes to achieve a particular goal. Mindfulness meditators perform better than non-meditators on numerous attention tasks, including the Stroop task, the d2-concentration and endurance test, and several others (Jha, Krompinger, & Baime, 2007; Moore & Malinowski, 2009; Slagter et al., 2007; Tang et al., 2007; van den Hurk, Giommi, Gielen, Speckens, & Barendregt, 2010). They also exhibit enhanced event-related potential (ERP) indices of attention and performance monitoring relative to non-meditators, suggesting stronger attention abilities (Larson, Steffen, & Primosch, 2013; Moore, Gruber, Derose, & Malinowski, 2012; Teper & Inzlicht, 2013a). Similarly, in a study utilizing functional magnetic resonance imaging (fMRI), Kozasa et al. (2012) found that regular meditators showed decreased brain activation during an fMRI-adapted color-word Stroop task compared to non-meditators, with no differences in performance, indicating that mindfulness may improve efficiency of cognitive resource allocation through improved sustained attention and impulse control. Yet, the neural mechanism through which mindfulness enhances cognitive control is not well understood.

1.2 Frontal Midline Theta

Recent advances in cognitive neuroscience have led to the delineation of a candidate neural mechanism that may serve cognitive control processes, frontal midline theta (FMθ). FMθ refers to oscillations in the primate electroencephalogram (EEG) occurring at approximately 4-8 Hz, or cycles per second, recorded from sensors overlying the medial prefrontal cortex (mPFC). It ostensibly signals the need for top-down cognitive control and may be the mechanism by which neurons could compute

and communicate top-down control across broad networks (Cavanagh & Frank, 2014; Cavanagh, Zambrano-Vazquez, & Allen, 2012). Several ERP components are thought to represent similar mPFC-related control processes evoked by novel information (N2 component), conflicting stimulus-response demands (N2 component), punishing feedback (feedback-related negativity component; FRN), and the commission of errors (error-related negativity component; ERN; for a review, see Cavanagh & Frank, 2014). These ERPs are united not only in that they are evoked by events that require increased cognitive control, but also by their common spectral signature in the theta frequency band (~4-8 Hz).

ERP studies of mindfulness have shown that meditators exhibit larger N2 amplitudes in response to conflicting stimuli (Moore et al., 2012), larger ERN amplitudes in response to the commission of errors (Teper & Inzlicht, 2013a), and smaller FRN amplitudes in response to negative feedback (Teper & Inzlicht, 2013b). Because these ERP components are thought to be comprised of FMθ oscillations (see Cavanagh & Frank, 2014), these findings suggest that mindfulness may improve cognitive control through enhancement of FMθ; It should be noted, however, that ERPs, which represent evoked EEG activity, do not necessarily reflect induced oscillatory rhythms, such as FMθ.

1.3 Induced Activity vs. Evoked Activity

Induced activity can best be considered rhythmic background activity that is modulated, rather than evoked, by the onset of experimental stimuli or other events (Pfurtscheller & Lopes da Silva, 1999). As Bastiaansen, van Berkum, and Hagoort (2002) note, a well-known and well-studied example of induced activity is the observable power increase of the occipital alpha rhythm (~9-13 Hz) by the closing of

the eyes (e.g., Berger, 1929). Importantly, induced activity has a fixed temporal relation to an event (e.g., closing the eyes immediately leads to an increase in alpha power) without being necessarily phase-locked to the event (e.g., alpha power is always enhanced after closing the eyes, regardless of the alpha oscillations' phase at the moment of eye closure). Evoked activity, on the other hand, is both time- and phase-locked to the event, in some cases due to the phase resetting of oscillations in response to the event (e.g., Yeung, Bogacz, Holroyd, Nieuwenhuis, & Cohen, 2007). Because of the relatively low signal-to-noise ratio inherent to EEG recordings, it is common practice in ERP research to average EEG signals over a number of trials. This procedure has two important consequences: 1) it substantially improves the signal-to-noise ratio of the ERP and 2) it destroys any temporal structure in the EEG signal that is not both time-locked and phase-locked to the experimental event (Tallon-Baudry & Bertrand, 1999). Thus, only evoked activity, which is both time- and phase-locked to the experimental event, is preserved in the averaged ERP. Meanwhile, induced activity cancels itself out during averaging because the inconsistency of its phases across multiple trials causes signal peaks to be averaged with signal troughs.

1.4 The Current Study

To date, all known electrophysiological studies of mindfulness and cognitive control have relied on the intertrial-averaging procedure inherent to ERP analyses, which, as noted above, eliminates induced activity and therefore results in poor measurement of FMθ. The aim of the present study is to test the association between mindfulness and a direct measure of FMθ (event-related spectral perturbations; ERSP) obtained during an attentionally-demanding task. Because mindfulness is associated with enhanced cognitive control, it is hypothesized that mindfulness will be positively

associated with FMθ power following presentation of conflicting stimuli and following error commission, two conditions that increase the need for cognitive control.

Chapter 2

METHOD

2.1 Participants

Twenty-four volunteers (75% female, 87.5% Caucasian, mean age ± *SD* = 20.1 ± 1.4) were recruited for the present EEG study from an undergraduate psychology class at the University of Delaware. All students whose native language was English were invited to participate. For their participation, students received extra credit in their psychology class. No subject discontinued his/her participation once informed consent was obtained and the procedures began. EEG data from four participants were not included in error-related analyses due to having fewer than eight artifact-free error trials (Olvet & Hajcak, 2009).

2.2 Task

All participants completed a modified version of the flanker task (Eriksen & Eriksen, 1974) on a Dell Dimension DE051 desktop computer using Presentation software version 10.0 (Neurobehavioral Systems, Inc.) to control the presentation and timing of all stimuli, the identification of responses, and the measurement of reaction times. During the task, participants were shown horizontal sequences of letters in the center of a 17” CRT monitor. Letters were presented in white font on a black background. Participants were instructed to identify the middle letter, which was flanked by two distractor letters on each side. Participants responded to the target letter by pressing left and right buttons on a Cedrus button box with their left and right hands, respectively.

The task consisted of 600 trials of confusable letter strings (e.g., MMMMM, MMNMM, NNMNN, and NNNNN) with letter combinations that varied from block

to block (i.e., MN, EF, OQ, VU, IT, and PR) across 15 blocks. Within each block, stimuli were presented randomly, with 50% congruent and 50% incongruent trials. During congruent trials, flanker letters were the same as the target (middle) letter (e.g., MMMMM). During incongruent trials, flanker letters were different from the target letter (e.g., MMNMM). The intertrial interval (ITI) varied randomly between 1,200 and 1,700 ms in 100-ms increments. Within each ITI, a fixation cross appeared first. It was then replaced by the flankers, appearing alone for 35 ms to capture the participant's attention. The target letter then appeared with the flankers and remained on the screen for 100 ms.

At the beginning of each block, an instruction screen was presented that identified the letters in the upcoming block, as well as the response button mapped to each letter. Each letter pair appeared for two consecutive blocks, with the button mapped to each letter reversed for the second block of each letter pairing.

2.3 Procedure

Following a brief description of the experiment, participants were fitted with an electrode cap. They were then given detailed task instructions. Each participant was seated approximately 0.5 m directly in front of the computer monitor and given one practice block, in which he/she had to make 20 correct responses. Participants were told to place equal emphasis on speed and accuracy in their responding. Following practice, participants began the experimental blocks, each of which was initiated by the participant.

After completing the flanker task, participants completed three questionnaires in Qualtrics. The Five Facet Mindfulness Questionnaire (FFMQ; Baer, Smith, Hopkins, Krietemeyer, & Toney, 2006) was administered to evaluate participants' trait

mindfulness. Because negative affect is thought to be linked to reduced cognitive control (e.g., Joormann & Vanderlind, 2014) and is negatively associated with mindfulness (e.g., Brown & Ryan, 2003), the Beck Depression Inventory-II (BDI-II; Beck, Steer, & Brown, 1996) and the Penn State Worry Questionnaire (PSWQ; Meyer, Miller, Metzger, & Borkovec, 1990) were also administered.

2.4 Electrophysiological Recording, Data Reduction, and Analysis

EEG was recorded from 30 Ag/Cl sintered electrodes embedded in an electrode cap with an average reference and forehead ground. EEG impedances were below 20 KΩ, and the data were digitized at 1,024 Hz using ANT acquisition hardware (Advanced Neuro Technology, Enschede, The Netherlands). Offline, continuous EEG was corrected for eye blinks with ASA software from ANT.

All of the following EEG data processing steps were accomplished with the MATLAB-based open source signal processing toolbox, FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011). First, epochs were extracted based on stimulus and response onsets. For stimulus-based analyses (i.e., incongruent vs. congruent trials), epochs were extracted from 2,100 ms pre-stimulus to 2,500 ms post-stimulus. Only trials with correct responses were included in the stimulus-based analyses. For response-based analyses (i.e., error vs. correct trials), epochs of the same length were extracted, but with respect to the button response. Epochs with such long durations were extracted in order to avoid edge artifacts that can be associated with power spectra calculation. Epochs were rejected if a button press was not made in the 800 ms following stimulus presentation. Next, muscle artifact rejection was accomplished with Z-transformations of the epoched EEG data. The data were band-pass filtered from 110 to 140 Hz with a Butterworth digital filter, Z-transformed, and averaged

across sensors. Epochs with Z-values exceeding a cutoff of 4 were considered to contain artifactual muscle activity and rejected.

ERSP analysis was performed according to the procedures described by Tallon-Baudry, Bertrand, Delpuech, and Permier (1997). Convolution with complex Morlet wavelets was applied to single trials in steps of 50 ms. The tradeoff between frequency and time resolution was determined by the constant m = 7 (determining the width of the wavelet in number of cycles). The time-frequency representation of power (TFR) was calculated by averaging the squared absolute values of the convolutions over trials. TFRs were expressed as decibels (dB) relative to baseline, which was defined as 600 ms pre-stimulus to stimulus onset for the stimulus-based analyses and 600 ms pre-response to 200 ms pre-response for the response-based analyses. For stimulus-based analyses, statistical analysis of the TFRs was confined to epochs from stimulus onset to 1,000 ms post-stimulus; for response-based analyses, it was confined to epochs from 200 ms pre-response to 600 ms post-response.

Chapter 3

RESULTS

3.1 Trial-Type Comparisons

In order to verify whether the flanker task successfully elicited FMθ activity, two cluster-based permutation tests were performed according to the procedures described by Maris and Oostenveld (2007): one contrasting congruent and incongruent trials and the other contrasting error and correct trials. TFR across 4-8 Hz was averaged together for these analyses. These permutation tests were conducted with the following steps: 1) for every sensor-time pair, the two conditions were compared with a dependent-sample t-test; 2) all pairs were selected whose test statistic was larger than the critical value where alpha is equal to .025; 3) the selected pairs were clustered in connected sets on the basis of temporal and spatial adjacency (a minimum of two pairs were required to form a cluster); 4) cluster-level statistics were calculated by taking the sum of the t-values within every cluster; 5) the maximum of the cluster-level statistics was calculated; and 6) the maximum and sum cluster-level statistics for each cluster were compared to a distribution of cluster-level statistics obtained from 5,000 randomizations in which each pair was shuffled across conditions. This last step resulted in a p-value for each observed cluster that was compared to an overall critical alpha level of .025.

In the incongruent vs. congruent trial contrast, one significant cluster (p = 0.0008) was observed and it had a predominantly central topography, indicating greater FMθ power for incongruent trials compared to congruent trials (see Figure 1).

In the error vs. correct trial contrast, one significant cluster (p = 0.0006) was observed and it also had a predominantly central topography, indicating greater FMθ power for error trials compared to correct trials (see Figure 2).

3.2 Path Analyses

Based on the centralized topography observed from the two within-subject contrasts described above, two FMθ power scores were obtained for each participant at sensor site Cz: one for incongruent trials and the other for error trials. These scores were measured as the peak FMθ power (greatest TFR between 4-8 Hz) during an average trial of each of the two trial types. A path analysis was then conducted using Mplus version 7.2 (Muthén & Muthén, 1998-2012). Incongruent-trial FMθ power and error-trial FMθ power were the outcome variables, while FFMQ, BDI-II, and PSWQ total scores were the predictor variables (for descriptive statistics and intercorrelations among variables, see Table 1; for path model estimates, see Table 2). The FFMQ's total score was used in lieu of its subscale scores because of the small sample size. Intercorrelations among the three predictor variables were high: FFMQ score was negatively correlated with BDI-II ($r(22) = -.71$, $p < .001$) and PSWQ ($r(22) = -.62$, $p < .001$) scores, and BDI-II score was positively correlated with PSWQ score ($r(22) = .53$, $p = .008$). Goodness of fit indices are not reported because the model was saturated, meaning that model fit was perfect because there were at least as many estimated parameters as data points. A saturated path model perfectly reproduces all of the variances, covariances, and means of the observed variables, much like a traditional regression model. For incongruent-trial FMθ power, there was an effect of BDI-II score (β = -0.134, p = .027, 95% CI = -0.252, -0.015) and a trend-level effect of FFMQ score (β = -0.030, p = .053, 95% CI = -0.061, 0.000). Thus, participants with

higher scores on the FFMQ or BDI-II tended to exhibit less FMθ power following incongruent stimuli. For error-trial FMθ power, there was an effect of FFMQ score (β = -0.073, p = .002, 95% CI = -0.120, -0.026) and a trend-level effect of BDI-II score (β = -0.184, p = .061, 95% CI = -0.377, 0.009). Therefore, participants with higher scores on the FFMQ or BDI-II tended to exhibit less FMθ power following error responses.

Because the path model above revealed negative relationships between FFMQ and both incongruent-trial FMθ power and error-trial FMθ power (contrary to hypotheses), a second path analysis was conducted with average reaction time and proportion of correct responses as the outcome variables and FFMQ, BDI-II, and PSWQ total scores as the predictor variables (for path model estimates, see Table 3). Goodness of fit indices are again not reported because this model was also saturated. For average reaction time, there was an effect of PSWQ score (β = 2.725, p = .019, 95% CI = 0.453, 4.996), so participants with higher PSWQ scores tended to respond more slowly. For proportion of correct responses, there was an effect of BDI-II score (β = -0.008, p = .037, 95% CI = -0.016, -0.001). That is, participants who scored higher on the BDI-II tended to make more errors on the flanker task.

Table 1

Descriptive Statistics and Intercorrelations

Measure	Min.	Max.	*M*	*SD*	1	2	3	4	5	6
1. Incongruent-trial FMθ power (dB)	1.52	5.72	3.75	1.17						
2. Error-trial FMθ power (dB)	1.44	8.21	4.11	1.85	.50*					
3. Average reaction time (ms)	262.39	522.88	404.60	61.78	-.27	-.27				
4. Proportion of correct responses	0.62	0.98	0.87	0.08	.00	.11	.53*			
5. Beck Depression Inventory-II	0	18	7.54	5.03	-.28	-.09	-.24	-.33		
6. Penn State Worry Questionnaire	28	78	48.71	12.28	-.14	-.14	.20	-.04	.53*	
7. Five Facet Mindfulness Questionnaire	90	169	135.46	20.89	-.03	-.27	.16	.09	-.71**	-.62**

Note. FMθ = Frontal Midline Theta. Error-trial FMθ power was not measured from four participants due to near perfect performance.
* $p < .05$. ** $p < .001$. All p-values are two-tailed.

Table 2

Estimates from Path Model for Incongruent-Trial and Error-Trial Frontal Midline Theta Power

Outcome: incongruent-trial FMθ power (dB)	Estimate (SE)	*p-value*	95% *CI*	
			Lower	Upper
Beck Depression Inventory-II	-0.134 (0.061)	.027	-0.252	-0.015
Penn State Worry Questionnaire	-0.016 (0.022)	.463	-0.060	0.027
Five Facet Mindfulness Questionnaire	-0.030 (0.016)	.053	-0.061	0.000
R^2	0.203 (0.147)	.165	-	-
Outcome: error-trial FMθ power (dB)	Estimate (SE)	*p-value*	95% *CI*	
			Lower	Upper
Beck Depression Inventory-II	-0.184 (0.098)	.061	-0.377	0.009
Penn State Worry Questionnaire	-0.049 (0.034)	.151	-0.116	0.018
Five Facet Mindfulness Questionnaire	-0.073 (0.024)	.002	-0.120	-0.026
R^2	0.301 (0.160)	.060	-	-

Note. FMθ = Frontal Midline Theta. Error-trial FMθ power was not measured from four participants due to near perfect performance. All p-values are two-tailed.

Table 3

Estimates from Path Model for Average Reaction Time and Proportion of Correct Responses

Outcome: average reaction time (ms)	Estimate (SE)	*p-value*	95% *CI*	
			Lower	Upper
Beck Depression Inventory-II	-4.317 (3.138)	.169	-10.468	1.835
Penn State Worry Questionnaire	2.725 (1.159)	.019	0.453	4.996
Five Facet Mindfulness Questionnaire	0.731 (0.817)	.371	-0.871	2.332
R^2	0.234 (0.151)	.122	-	-
Outcome: proportion of correct responses	Estimate (SE)	*p-value*	95% *CI*	
			Lower	Upper
Beck Depression Inventory-II	-0.008 (0.004)	.037	-0.016	-0.001
Penn State Worry Questionnaire	0.001 (0.001)	.687	-0.002	0.003
Five Facet Mindfulness Questionnaire	-0.001 (0.001)	.392	-0.003	0.001
R^2	0.160 (0.137)	.243	-	-

Note. All p-values are two-tailed.

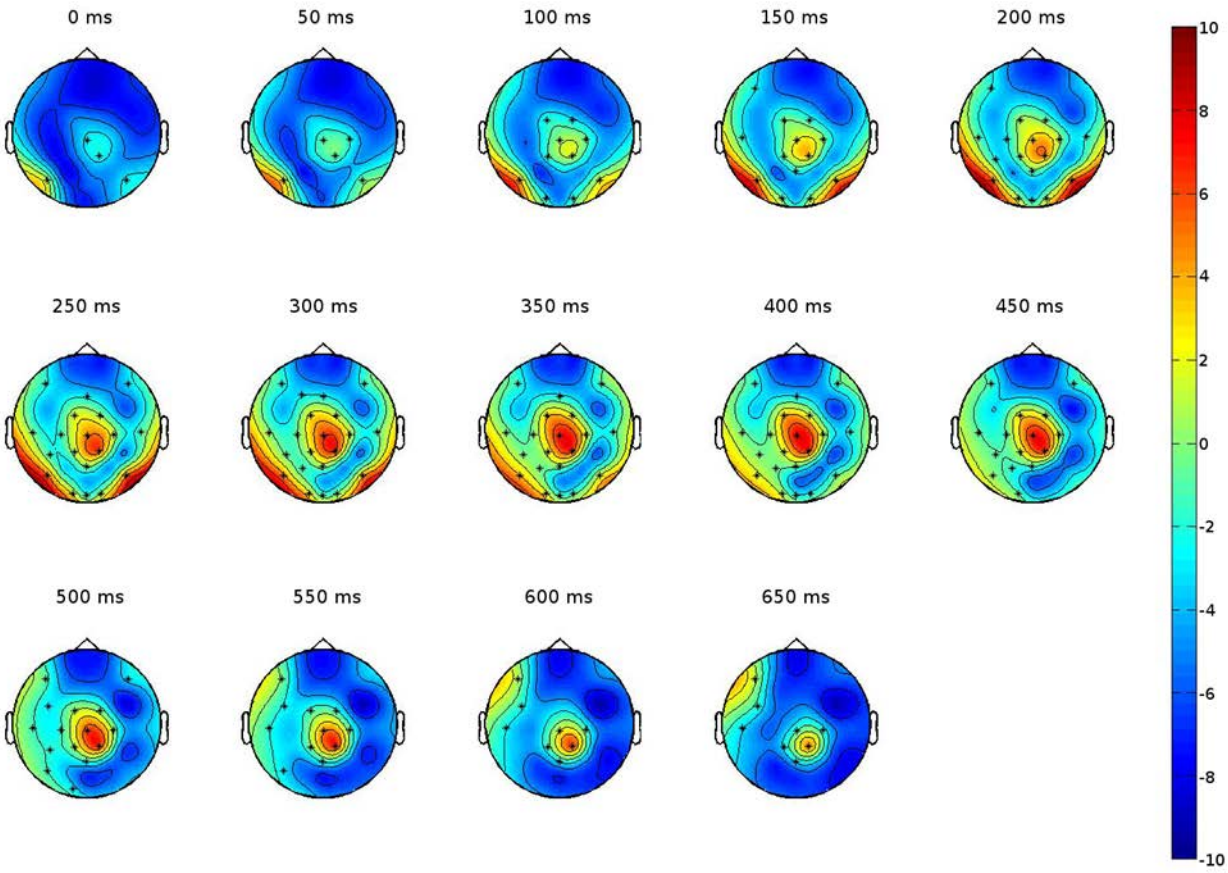

Figure 1. Results of Incongruent- vs. Congruent-Trial Theta Power Contrast. Times are relative to stimulus presentation. Colors represent t-values. Positive t-values indicate greater theta power during incongruent trials compared to congruent trials. Stars denote sensors that comprise the significant observed cluster ($p = 0.0008$).

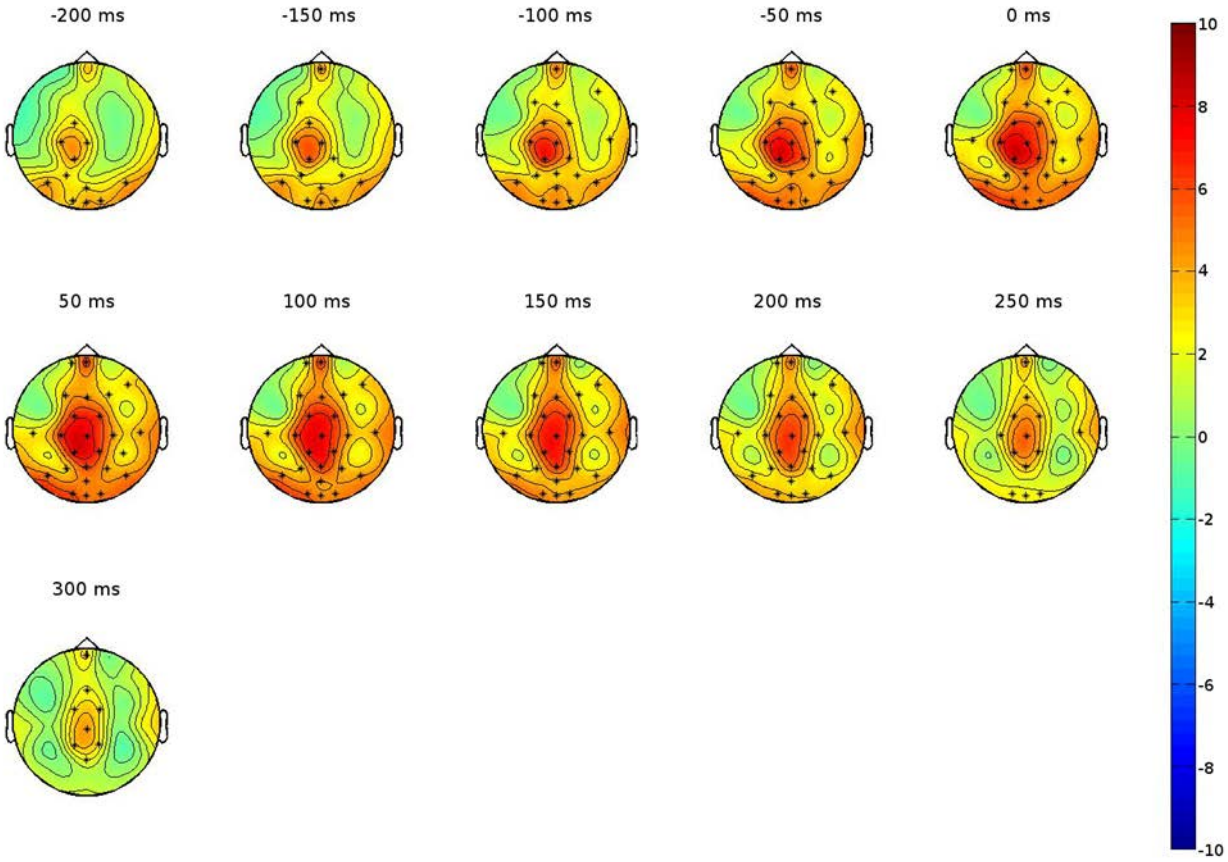

Figure 2. Results of Error- vs. Correct-Trial Theta Power Contrast. Times are relative to responses. Colors represent t-values. Positive t-values indicate greater theta power during error trials compared to correct trials. Stars denote sensors that comprise the significant observed cluster ($p = 0.0006$). Four participants were excluded from this contrast due to near-perfect performance.

Chapter 4

DISCUSSION

The current study aimed to test whether mindfulness was associated with enhanced FMθ power – a putative measure of brain activity signaling the need for cognitive control – following the presentation of conflicting stimuli (incongruent letters) and following the commission of errors. Before testing this hypothesis, it was important to first confirm that the flanker task successfully elicited FMθ activity. This was verified by two within-subject, trial-type comparisons that showed greater theta-band power following incongruent (vs. congruent) stimuli and error (vs. correct) responses. Contrary to the main hypothesis, however, mindfulness scores negatively predicted FMθ power following both conflicting stimuli and error responses. Similarly, depression scores also negatively predicted FMθ power following both conflicting stimuli and error responses. The second path analysis revealed that worry scores predicted longer average reaction times and that depression scores negatively predicted participants' proportion of correct responses. Therefore, although both mindfulness and depression were associated with reduced FMθ power, depression was also associated with poorer performance. Because individuals with higher mindfulness scores tended to exhibit reduced FMθ power with no corresponding drops in performance, results suggest that mindfulness may be related to greater efficiency of cognitive control signaling. This could mean that individuals who are more mindful are somehow more attuned to these control signals, possibly through stronger oscillatory phase synchrony which is thought to reflect the coherence of neural

communication and information encoding (Canolty & Knight, 2010; Lisman, 2005; Jensen and Colgin, 2007). Additionally, this efficiency could be due to greater top-down control; however, improved top-down control would likely also result in better performance, which was not associated with mindfulness in this study. Overall, this efficiency interpretation is consistent with Kozasa and colleagues' (2012) findings that meditators showed decreased hemodynamic brain responses but no performance differences compared to non-meditators during a Stroop task. In contrast to mindfulness, however, depression may be related simply to poorer cognitive functioning because individuals with higher depression scores had both weaker FMθ responses and poorer performance. This is consistent with a host of studies showing that depression severity is associated with cognitive impairment (for a meta-analysis, see McDermott & Ebmeier, 2009).

4.1 Strengths and Limitations

The present study benefitted from the high temporal resolution afforded by the acquisition of EEG data, enabling the application of ERSP analysis to obtain valid measurements of FMθ power. Additionally, despite reliance on a relatively small undergraduate sample, there was sufficient variability in questionnaire scores, physiological measurements, and task performance to detect significant relationships with variables pertaining to mental health. Still, it is important to note that the entire range of possible self-report questionnaire scores was not well represented by this sample. This was particularly true in the case of the BDI-II, which has a maximum possible score of 63, while the maximum BDI-II score observed in the present study was only 18. This represents a potential study limitation as it is possible that the

relationships between depression scores and other key variables of interest are different at the higher range of depression scores. Similarly, the relative lack of gender and ethnic diversity in this sample also limit these findings' generalizability. Finally, another study limitation is that causality cannot be inferred from the present results; for example, it is impossible to determine from these data whether mindfulness or depression are caused by changes in cognitive control or vice-versa, or even whether they are both caused by a third variable.

4.2 Directions for Future Study

The current findings pave the way for several possible future directions. First, in order to reconcile these results with those of Teper and Inzlicht (2013a), who showed that mindfulness meditators exhibit larger ERN amplitudes, it should be tested whether mindfulness is related to greater intertrial FMθ phase consistency, which would lead to larger ERP amplitudes despite decreases in oscillatory power. Second, because a key feature of mindfulness is enhanced emotion regulation (see Hölzel et al., 2011), future studies should investigate the link between mindfulness and cognitive control-related brain activity during emotion regulation tasks. Third, although FMθ power appears to be the neural mechanism responsible for signaling the need for cognitive control, the mechanism that actually exerts that top-down cognitive control is less understood. As Cavanagh and Frank (2014) note, theta-band phase synchronization between brain areas is a biologically plausible candidate mechanism, and such synchronization has been observed following a variety of FMθ signals. Thus, it should be tested whether mindfulness is associated with stronger theta-band phase synchronization during tasks that require cognitive control. Lastly, future studies would likely benefit from distinguishing between the various facets of mindfulness in

order to gain a more detailed picture of how each facet relates to other important variables of interest.

REFERENCES

Baer, R. A. (2003). Mindfulness Training as a Clinical Intervention: A Conceptual and Empirical Review. *Clinical Psychology: Science and Practice, 10*(2), 125–143. doi:10.1093/clipsy.bpg015

Baer, R. A., Smith, G. T., Hopkins, J., Krietemeyer, J., & Toney, L. (2006). Using self-report assessment methods to explore facets of mindfulness. *Assessment, 13*(1), 27–45. doi:10.1177/1073191105283504

Bastiaansen, M. C. M., van Berkum, J. J. a., & Hagoort, P. (2002). Syntactic Processing Modulates the θ Rhythm of the Human EEG. *NeuroImage, 17*(3), 1479–1492. doi:10.1006/nimg.2002.1275

Beck, A. T., Steer, R. A., & Brown, G. K. (1996). *Manual for Beck Depression lnventory-II*. San Antonio, TX: Psychological Corporation.

Berger, H. (1929). Über das elektrenkephalogramm des menschen. *European Archives of Psychiatry and Clinical Neuroscience, 87*(1), 527–570.

Brown, K. W., & Ryan, R. M. (2003). The benefits of being present: Mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology, 84*(4), 822–848. doi:10.1037/0022-3514.84.4.822

Canolty, R., & Knight, R. (2010). The functional role of cross-frequency coupling. *Trends in Cognitive Sciences, 14*(11), 506–515. doi:10.1016/j.tics.2010.09.001.The

Cavanagh, J. F., & Frank, M. J. (2014). Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences, 18*(8), 414–421. doi:10.1016/j.tics.2014.04.012

Cavanagh, J. F., Zambrano-Vazquez, L., & Allen, J. J. B. (2012). Theta lingua franca: a common mid-frontal substrate for action monitoring processes. *Psychophysiology, 49*(2), 220–38. doi:10.1111/j.1469-8986.2011.01293.x

Eriksen, B., & Eriksen, C. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143–149.

Hayes, A. M., Beevers, C. G., Feldman, G. C., Laurenceau, J.-P., & Perlman, C. (2005). Avoidance and processing as predictors of symptom change and

positive growth in an integrative therapy for depression. *International Journal of Behavioral Medicine,12*(2), 111–22. doi:10.1207/s15327558ijbm1202_9

Hayes, S. C., Strosahl, K. D., & Wilson, K. G. (1999). *Acceptance and commitment therapy*. New York: Guilford Press.

Hölzel, B. K., Lazar, S. W., Gard, T., Schuman-Olivier, Z., Vago, D. R., & Ott, U. (2011). How does mindfulness meditation work? Proposing mechanisms of action from a conceptual and neural perspective. *Perspectives on Psychological Science, 6*(6), 537–559. doi:10.1177/1745691611419671

Jensen, O., & Colgin, L. L. (2007). Cross-frequency coupling between neuronal oscillations. *Trends in Cognitive Sciences, 11*(7), 267–9. doi:10.1016/j.tics.2007.05.003

Jha, A. P., Krompinger, J., Baime, M. J. (2007). Mindfulness training modifies subsystems of attention. *Cognitive, Affective, & Behavioral Neuroscience, 7*(2), 109–119.

Joormann, J., & Vanderlind, W. M. (2014). Emotion regulation in depression: The role of biased cognition and reduced cognitive control. *Clinical Psychological Science, 2*(4), 402–421. doi:10.1177/2167702614536163

Kabat-Zinn, J. (1990). *Full catastrophe living: Using the wisdom of your body and mind to face stress, pain, and illness*. New York, NY: Delta.

Kozasa, E. H., Sato, J. R., Lacerda, S. S., Barreiros, M. A. M., Radvany, J., Russell, T. a, … Amaro, E. (2012). Meditation training increases brain efficiency in an attention task. *NeuroImage, 59*(1), 745–9. doi:10.1016/j.neuroimage.2011.06.088

Larson, M. J., Steffen, P. R., & Primosch, M. (2013). The impact of a brief mindfulness meditation intervention on cognitive control and error-related performance monitoring. *Frontiers in Human Neuroscience, 7*(July), 308. doi:10.3389/fnhum.2013.00308

Linehan, M. (1993). *Cognitive-behavioral treatment of borderline personality disorder*. New York: Guilford Press.

Lisman, J. (2005). The theta/gamma discrete phase code occuring during the hippocampal phase precession may be a more general brain coding scheme. *Hippocampus, 15*(7), 913–22. doi:10.1002/hipo.20121

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164*(1), 177–90. doi:10.1016/j.jneumeth.2007.03.024

Marlatt, G. A., & Gordon, J. R. (1985). *Relapse prevention: Maintenance strategies in addictive behavior change*. New York: Guilford Press.

McDermott, L. M., & Ebmeier, K. P. (2009). A meta-analysis of depression severity and cognitive function. *Journal of Affective Disorders, 119*(1-3), 1–8. doi:10.1016/j.jad.2009.04.022

Meyer, T. J., Miller, M. L., Metzger, R. L., & Borkovec, T. D. (1990). Development and validation of the Penn State Worry Questionnaire. *Behaviour Research and Therapy, 28*(6), 487–495. doi:10.1016/0005-7967(90)90135-6

Moore, A., Gruber, T., Derose, J., & Malinowski, P. (2012). Regular, brief mindfulness meditation practice improves electrophysiological markers of attentional control. *Frontiers in Human Neuroscience, 6*(February), 18. doi:10.3389/fnhum.2012.00018

Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and Cognition, 18*(1), 176–86. doi:10.1016/j.concog.2008.12.008

Muthén, L.K. & Muthén, B.O. (1998-2012). *Mplus User's Guide. Seventh Edition.* Los Angeles, CA: Muthén & Muthén

Olvet, D. M., & Hajcak, G. (2009). The stability of error-related brain activity with increasing trials. *Psychophysiology, 46*(5), 957–61. doi:10.1111/j.1469-8986.2009.00848.x

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience, 2011*. doi:10.1155/2011/156869

Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clinical Neurophysiology, 110*(11), 1842–1857. doi:10.1016/S1388-2457(99)00141-8

Slagter, H. A., Lutz, A., Greischar, L. L., Francis, A. D., Nieuwenhuis, S., Davis, J. M., & Davidson, R. J. (2007). Mental training affects distribution of limited brain resources. *PLoS Biology, 5*(6), e138. doi:10.1371/journal.pbio.0050138

Tallon-Baudry, C., & Bertrand, O. (1999). Oscillatory gamma activity in humans and its role in object representation. *Trends in Cognitive Sciences*, *3*(4), 151–162.

Tallon-Baudry, C., Bertrand, O., Delpuech, C., & Permier, J. (1997). Oscillatory gamma-band (30-70 Hz) activity induced by a visual search task in humans. *The Journal of Neuroscience*, *17*(2), 722–34.

Tang, Y.-Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., … Posner, M. I. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(43), 17152–6. doi:10.1073/pnas.0707678104

Teasdale, J. D., Segal, Z., & Williams, J. M. G. (1995). How does cognitive therapy prevent depressive relapse and why should attentional control (mindfulness) training help? *Behaviour Research and Therapy*, *33*(I), 25–39.

Teper, R., & Inzlicht, M. (2013a). Meditation, mindfulness and executive control: the importance of emotional acceptance and brain-based performance monitoring. *Social Cognitive and Affective Neuroscience*, *8*(1), 85–92. doi:10.1093/scan/nss045

Teper, R., & Inzlicht, M. (2013b). Mindful acceptance dampens neuroaffective reactions to external and rewarding performance feedback. *Emotion*, *14*(1), 105–14. doi:10.1037/a0034296

van den Hurk, P. a. M., Giommi, F., Gielen, S. C., Speckens, A. E. M., & Barendregt, H. P. (2010). Greater efficiency in attentional processing related to mindfulness meditation. *The Quarterly Journal of Experimental Psychology*, *63*(6), 1168–1180. doi:10.1080/17470210903249365

Yeung, N., Bogacz, R., Holroyd, C. B., Nieuwenhuis, S., & Cohen, J. D. (2007). Theta phase resetting and the error-related negativity. *Psychophysiology*, *44*(1), 39–49. doi:10.1111/j.1469-8986.2006.00482.x

Appendix

IRB APPROVAL LETTERS

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE: March 25, 2014

TO: Emilio Valadez, B.A.
FROM: University of Delaware IRB

STUDY TITLE: [586731-1] Attentional control-related brain activity in mindful individuals during a flanker task

SUBMISSION TYPE: New Project

ACTION: APPROVED
APPROVAL DATE: March 25, 2014
EXPIRATION DATE: March 24, 2015
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category # *4,7*

Thank you for your submission of New Project materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

If you have any questions, please contact Nicole Farnese-McFarlane at (302) 831-1119 or nicolefm@udel.edu. Please include your study title and reference number in all correspondence with this office.

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE: April 28, 2014

TO: Emilio Valadez, B.A.
FROM: University of Delaware IRB

STUDY TITLE: [586731-2] Attentional control-related brain activity in mindful individuals during a flanker task

SUBMISSION TYPE: Amendment/Modification

ACTION: APPROVED
APPROVAL DATE: April 28, 2014
EXPIRATION DATE: March 24, 2015
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category # *(4, 7)*

Thank you for your submission of Amendment/Modification materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

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Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

If you have any questions, please contact Nicole Farnese-McFarlane at (302) 831-1119 or nicolefm@udel.edu. Please include your study title and reference number in all correspondence with this office.

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE: March 23, 2015

TO: Emilio Valadez, B.A.
FROM: University of Delaware IRB

STUDY TITLE: [586731-3] Attentional control-related brain activity in mindful individuals during a flanker task

SUBMISSION TYPE: Continuing Review/Progress Report

ACTION: APPROVED
APPROVAL DATE: March 23, 2015
EXPIRATION DATE: March 24, 2016
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category # *(4,7)*

Thank you for your submission of Continuing Review/Progress Report materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

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Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

If you have any questions, please contact Nicole Farnese-McFarlane at (302) 831-1119 or nicolefm@udel.edu. Please include your study title and reference number in all correspondence with this office.