EXAMINING HOW REGULAR MEDITATION PRACTICE INFLUENCES THE NEURAL OSCILLATORY ACTIVITY ASSOCIATED WITH REFOCUSING ATTENTION AFTER A MIND WANDERING EPISODE

by

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ABSTRACT

SPENCER FIX. Examining how regular meditation practice influences the neural oscillatory activity associated with refocusing attention after a mind wandering episode. (Under the direction of DR. MARK FAUST)

Introduction. Mind wandering (MW) has become a topic of interest in neuroscience research, particularly because of its tendency to interrupt goal directed behavior and negatively impact mental and physical health. Several brain networks have been implicated in the generation and suppression of MW, including the default mode network (DMN), fronto-parietal control network (FPCN), and dorsal attention network (DAN). Furthermore, meditation practices have been found to be associated with an increased ability to suppress MW and maintain focused attention. To examine the effects of meditation on the interactions between these three networks, comparisons were made in electroencephalographic (EEG) activity and self-report incidences of mind wandering. Methods. A between-groups design was used to investigate differences in event-related spectral perturbations (ERSP), an EEG measure of neural activity and inhibition, between a novice meditator and regular meditator group. Additionally, an independent component analysis was conducted to identify nodes of the DMN, FPCN, and DAN so that the ERSP changes associated with each network can be detected. Lastly, a functional connectivity analysis was conducted to examine the correlation in activity between networks. Results. Both groups displayed significant increases in alpha, beta, and gamma band activity and decreases in delta and theta activity following awareness of MW. Connectivity results suggest activation changes represented the FPCN and DMN coordinating to suppress MW and refocus attention. Though few activation differences were observed between groups, meditators produced lower connectivity between several pairs of network nodes than did novice meditator participants, suggestive of enhance neural efficiency.

Conclusion. The present study provides preliminary support for the use of independent component analysis in separating the activity of disparate neural network nodes. Finally, a robust activation pattern was replicated from a previous study which, when combined with the current connectivity results, represents reliable changes in network activity associated with MW suppression and attention refocusing.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

MW	mind wandering
DMN	default mode network
DAN	dorsal attention network
FPCN	fronto-parietal control network
EEG	electroencephalography
ERSP	event-related spectral perturbation
ERD	event-related desynchronization
ERS	event-related synchronization
sICA	spatial independent component analysis
IC	independent component
SART	sustained attention to response task
fMRI	functional magnetic resonance imaging
BOLD	bold oxygen level dependent
FAM	focused attention meditation
BC	breath counting
Hz	hertz
RQ	research question
3D	three dimensional
KOhm	kiloOhms
uV	microvolts
SD	standard deviation

M	mean
PFC	prefrontal cortex
ACC	anterior cingulate cortex
PCC	posterior cingulate cortex
IPC	inferior parietal cortex
PPC	posterior parietal cortex
AI	anterior insula
M1	sensorimotor cortex
d	dorsal
v	ventral
m	medial
l	lateral
p	posterior
ANOVA	analysis of variance
MNI	Montreal Neurological Institute

CHAPTER 1: INTRODUCTION

Our ability to stay focused is critically important for a wide variety of activities. When our attention is focused, relevant stimuli are processed more efficiently and task-unrelated mental activity is minimized. Despite our best efforts to stay focused, attention can drift away from the task at hand in a mind wandering (MW) episode. Though intentional MW (e.g., daydreaming) has been associated with adaptive functions like creativity and problem solving (Baird, Smallwood, Mrazek, Kam, Franklin, & Schooler, 2012; Gerlach, Spreng, Gilmore, & Schacter, 2011), unintentional MW can intrude on daily activities and impede performance on important tasks. A growing body of scientific literature has begun examining MW and its effects on cognitive, affective, social, and professional functioning, along with the neural mechanisms involved in MW generation and suppression (Andersen, Moore, Venables, & Corr, 2009; Anticevic, Cole, Murray, Corlett, Wang, & Krystal, 2012; Christoff, Gordon, Smith, & Vancouver, 2011; Goldin, Ramel, & Gross, 2009; McVay, & Kane, 2010; Sahdra et al., 2011).

Recent studies have found a negative correlation between cognitive control capabilities and the frequency of unwanted MW episodes (for a review, see Randall, Oswald, & Baier, 2014). Cognitive control, the ability to coordinate thoughts and actions in relation to internal goals, largely determines how often MW occurs, and researchers and clinicians have developed and evaluated a variety of training protocols designed to improve attention stability and reduce unwanted MW. Meditation training has emerged as a possible MW reduction strategy, in part because many meditation exercises directly improve cognitive control through enhanced attention stability (Lutz, Slagter, Rawlings, Drancis, Greischar, & Davidson, 2009; Sood & Jones, 2013; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010). Meditation also aims to minimize superfluous mental activity by bolstering one's ability to quickly identify and suppress MW (Wallace, 2006), which makes meditation an ideal candidate for studying the neural mechanisms involved in MW and cognitive control. By examining the neural activity surrounding the refocusing of attention after a MW episode during meditation, insight can be gained into how different brain networks interact to generate and suppress MW. Additionally, it is possible that investigating the neural mechanisms involved in MW and focused attention during meditation could contribute to our understanding of how meditation changes brain dynamics and how it leads to the cornucopia of positive effects found in recent studies (Slagter, Davidson, & Lutz, 2011).

Mind Wandering

The field of MW research has rapidly grown over recent years, and careful study has facilitated many advances in our understanding of what MW is and how it relates to other cognitive processes. Mind wandering is most prevalent when cognitive demands are low, as our ongoing stream of consciousness can meander from one thought to the next with fluidity and ease. These trains of thought will often start automatically without us being aware that we have lost our focus of attention. Mind wandering is also associated with being less engaged with the external world, a term called perceptual decoupling, which lasts until meta-awareness is achieved (Schooler, Smallwood, Christoff, Handy, Reichle, & Sayette, 2011). Eventually, meta-awareness occurs and we become aware that our mind has been wandering, which allows us the opportunity to refocus our attention or continue daydreaming.

The ubiquity of MW has become a topic interest for researchers in a variety of fields, as it can be quite distracting and can hamper task performance (Mooneyham, & Schooler, 2013). Though there is some debate as to whether MW necessarily represents a failure of cognitive control (McVay, & Kane, 2010; Smallwood, 2010; Watkins, 2010), current theories usually view MW as a distracting force that impedes task performance and goal directed action by tying up global cognitive resources like attention and working memory (Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Gruberger, Ben-Simon, Levkovitz, Zangen, & Hendler, 2011; Randall et al., 2014). Indeed, MW-related errors have been observed in a variety of cognitive tasks, including go-no-go (Cheyne, Solman, Carriere, & Smilek, 2009), reading (Storm., & Bui, 2016), signal detection (Kam et al., 2016), and driving (Qu, Ge, Xiong, Carciofo, Zhao, & Zhang, 2015) tasks. There is also growing empirical support for the notion that, because MW tends to draw attention away from the present moment, higher rates of MW are associated with negative mood states (Killingsworth & Gilbert, 2010; Marchetti, Koster, & Raedt, 2012; Poerio, Totterdell, & Miles, 2013; Smallwood, Fitzgerald, Miles, & Philips, 2009). The relationship between MW and negative mood states appears to be reciprocal, as heightened levels of one often leads to increases in the other (Poerio et al., 2013; Smallwood, & O'Connor, 2011; Smallwood, O’Connor, Sudbery, & Obonsawin, 2007).

Levels of self-related cognitive processing are crucial to consider when examining the association between MW and depressed mood. Indeed, experimental evidence suggests MW tends to be self-referential (Baird, Smallwood, & Schooler, 2011; Brewer, Garrison, & Whitefield-Gabrieli, 2013; Callard & Margulies, 2011) and more negatively-valanced (Killingsworth & Gilbert, 2010; Marchetti et al., 2012). One theory of self-identity has postulated that MW is necessarily more self-referential because the constant associations to, and reminders about, the self helps to solidify the feeling of self-continuity (Fingelkurts, & Fingelkurts, 2011). The overlap between self-referential processing and MW has been further validated by neuroscientific studies which have found similar areas in the brain are activated during both types of mental activities (Gusnard, Akbudak, Shulman, & Rachle, 2001)

The Wandering Brain

As external demands diminish, the mind tends to wander to self-related topics and a broad network within the brain is consistently activated. The realization that the brain is not completely inactive during periods of rest inspired the first studies on spontaneous and task-unrelated mental activity (Raichle et al., 2001). A relatively stable pattern of neural activity was found across studies during periods when participants were not actively engaged in a task. Furthermore, the same pattern of activity emerged during tasks when engagement or demands were low. Raichle and colleagues (2001) suggested that the default mode of the human mind was dominated by spontaneous and self-referential MW, so the brain network repeatedly found to be associated with MW was dubbed the default mode network (DMN). More recent research has buttressed the notion that a major role of the DMN is to support self-referential processing, as DMN activity has been associated with autobiographical memory (Spreng & Grady, 2010), processing self-related stimuli (Qin, & Northoff, 2011), and judging oneself (Whitfield-Gabrieli et al., 2011). The DMN (see Figure 7) has been associated with increased activation and functional connectivity between the medial prefrontal cortex (mPFC), the anterior (ACC) and posterior cingulate cortices (PCC), the posterior parietal cortex (PPC), the precuneus, and the lateral temporal cortex (Buckner, Andrews-Hanna, & Schacter, 2008). Though subtle subdivisions of the DMN have been proposed, recent studies suggest the mPFC and PCC compose the core of the network that is involved in all self-referential MW (Brewer, Garrison, & Whitefield-Gabrieli, 2013).

The study of neural activity involved in task engagement and externally-oriented attention has led to the identification of several brain networks that cooperatively or competitively interact depending on task demands. When a task requires an external focus of attention, the dorsal attention network (DAN) is recruited to support performance by activating the frontal eye fields, intraparietal sulcus, superior parietal complex, and middle temporal motion complex (Vincent, Kahn, Snyder, Raichle, & Buckner, 2008). These brain areas (see Figure 8) are involved in several aspects of externally focused attention, including signal detection, advanced sensory processing, and performance monitoring.

Anatomically situated between, and highly connected to, the DMN and the DAN is the frontoparietal control network (FPCN), which includes the dorsolateral and rostrolateral prefrontal cortices, middle frontal gyrus, anterior insula/frontal operculum, dorsal ACC, precuneus, and anterior inferior parietal lobule (Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013). An emerging view places the FPCN (see Figure 9) as the executive control system that orchestrates the activity of the DMN and the DAN depending on task demands. Recent studies have found high functional connectivity (i.e., positively correlated activity) between the FPCN and DMN, and low functional connectivity (i.e., negatively correlated activity) between the FPCN and DAN during periods of rest, internally oriented attention, and MW (Gao & Lin, 2012; Garrison et al., 2013a; Smallwood, Brown, Baird, & Schooler, 2012; Spreng et al., 2013). Conversely, low functional connectivity between the FPCN and DMN and high functional connectivity between the FPCN and DAN has been found during tasks that require externally oriented attention and when MW needs to be suppressed. Additionally, anatomical connectivity analyses have further supported this view by demonstrating the lack of direct neural connections between the DAN and DMN, while the FPCN has both independent areas and nodes that it shares with either the DAN or the DMN (Spreng et al., 2013). In summary, task demands and attention orientation largely determine whether the DAN or DMN is activated, while the FPCN is activated any time executive control is needed.

Measuring Mind Wandering

Neuroscientific studies have become increasingly sophisticated in how they measure and induce MW. Initially, all the neural activity that occurred during the relatively long rest periods in between tasks was averaged together and attributed to MW (Buckner et al., 2008). This average activity was then compared to the average activity that was generated during attention demanding tasks, resulting in rough estimates of the brain areas involved in MW and focused attention. More recently, continuous performance tasks like the Sustained Attention to Response Task (SART) have been used to carefully link DMN activity with more discrete episodes of MW (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; McVay & Kane, 2011; Zordan, Sarlo, & Stablum, 2008). During the SART, which requires participants to respond to numerous non-target stimuli and withhold their response to rare target stimuli, errors of commission are used as a marker for when task engagement is low and MW is likely to have just occurred (Cheyne, Solman, Carriere, & Smilek, 2009).

The use of active tasks like the SART can facilitate the direct comparison of neural activity associated with refocusing attention after episodes of MW. To ensure the reliable indexing of MW episodes during the SART, Christoff and colleagues (2011) asked participants whether or not they knew they were MW during specific periods of the task so that this subjective data could be used to differentiate between types of MW. This strategy allowed MW episodes to be separated by whether or not participants had meta-awareness of their own MW. Functional magnetic resonance imaging (fMRI) results indicated the DMN and FPCN were more active during self-reported MW than was observed when participants were actively focused on the task. Paradoxically, MW without awareness led to more robust activations in the DMN and FPCN than when participants were aware of their own MW. The authors suggest that the increased FPCN activation during MW without awareness may represent the executive control system attempting to suppress MW and refocus attention on to the task. Unfortunately, the use of active tasks, like the SART, may cloud results of MW as brain areas associated with the active components of the task (e.g., signal detection) are likely to be co-activated throughout the task. Furthermore, fMRI data was averaged by Christoff and colleagues (2011) over a period of ten seconds, so it was impossible to closely examine the time course of how the two networks interacted.

Electroencephalographic (EEG) imaging has a much higher temporal resolution than fMRI, so it has greater potential for carefully examining how the neural dynamics associated with MW and focused attention unfold over time. Because EEG imaging directly measures brain activity, instead of the blood flow changes seen with fMRI, it is possible to detect minute fluctuations in neural activity across the range of established EEG frequency bands (delta < 4 Hz, theta 4–7 Hz, alpha 8–12 Hz, beta 12-30 Hz, Gamma 30-100Hz) that have been associated with different cognitive functions (Kahana, 2006). By separating neural activity on the dimensions of time and frequency, the synchronization and desynchronization that occurs between groups of neurons at different locations in the brain can be used to estimate changes in network interactions across time (Pfurtscheller & Lopes da Silva, 1999).

Event-Related Spectral Perturbations and Mind Wandering

Event-related spectral perturbation (ERSP) analyses have been used to compare the EEG activity in the time-frequency domain that occurs before and after an awareness of MW event. By time-locking EEG data to an event (e.g., MW meta-awareness), the averaged activity within specific EEG frequency bands can be tracked across time in relation to the target event. Researchers have used ERSP as a global term to include event-related desynchronizations (ERD) and event-related synchronizations (ERS), which compare the EEG activity before and after an event to estimate the relative increase or decrease in synchronized neuronal firing across a range of frequencies. Generally speaking, if a target event (e.g., MW meta-awareness) signals the recruitment of new cognitive resources (e.g., focused attention), an ERS from brain areas supporting that new cognitive function (e.g., FPCN) would be expected as a representation of increased neural activity and communication. Conversely, when a cognitive process is not needed for a particulate event (e.g., self-referential processes), or when it may interfere with new cognitive resources being recruited, and ERD is likely to occur (e.g., within the DMN) to signal the fading of activity and communication associated with that cognitive resource. It should be noted that when evaluating the results from an ERSP analysis, it is crucial to understand the specific mental activity that will occur before and after the event because ERSP results are framed as a comparison in activity between two time periods.

Braboszcz and Delorme (2011) used an ERSP analysis to investigate periods of MW and focused attention during a breath counting (BC) task. Instead of being asked to respond to external stimuli, like in the SART, participants in this experiment were instructed to count their breaths and to press a button each time they became aware that they had lost count or noticed their mind had wandered away from counting. Using a discrete and time sensitive marker (i.e., a button press) of the participant's meta-awareness of their MW facilitated the examination of how brain activity changed in relation to this event in each EEG frequency band (see Figure 1). Results indicated lower power in the occipital alpha (8-12 Hz) and fronto-lateral beta (12-30 Hz) band frequencies was associated with periods of MW when compared to the focused attention period immediately after the button press. These results are in direct contrast to two studies that correlated fMRI and EEG activity during an eyes-closed rest period and found that decreases in alpha power were associated with FPCN activation and increased beta power was associated with DMN activation (Laufs et al., 2003a; 2003b). Though high alpha power is usually associated with brain areas idling due to inactivity, some studies have found that increased working memory load can lead to higher alpha power (Jensen, Gelfand, Kounios, & Lisman, 2002; Klimesch, 2012).

Braboszcz and Delorme (2011) also found MW was associated with higher power in the theta band (4-8 Hz) over occipital and parieto-central regions and in the delta band (<4 Hz) over fronto-central regions, which may have indicated increased coupling of the DMN and FPCN at their shared connections in the inferior parietal cortex and mPFC. In contrast to the above findings, high theta power has been previously linked to DMN suppression (Meltzer, Negishi, Mayes, & Constable, 2007; Scheeringa et al., 2008) and increased attentional engagement (Chang & Huang, 2012), though these studies found theta increases were centered on the frontal midline region instead of more posterior regions. The higher delta power found is also controversial, as delta activity has usually been linked to signal detection and decision-making (Kamarajan et al., 2004). It may be that the high delta signified the FPCN attempting to connect with the DAN to reinitiate performance monitoring.

Unfortunately, relatively few studies have utilized ERSP analyses to investigate MW, so only preliminary conclusions can be drawn between frequency-specific changes in activation, neural network interactions, and cognitive processes. Furthermore, it should be noted that results from an ERSP analysis are comparative in nature, such that the neural activations associated with MW can only be identified in relation to the activations that occur after the button press indicating a return to focused attention. Thus, utilizing a task that is relatively simple and requires very few cognitive resources be recruited to maintain task performance is essential for providing the clearest comparison between MW and focused attention.

Mind Wandering and Meditation in the Brain

In parallel with studies examining the positive effects of meditation on health and well-being (Hussain & Bhushan, 2010; Kok, Waugh, & Fredrickson, 2013), recent research has begun using meditation to investigate the neural mechanisms involved in MW and focused attention. Some researchers have suggested focused attention meditation (FAM), as opposed to other meditation techniques (e.g., open monitoring) that that have a broader attentional focus, is the ideal task for inducing MW because this type of meditation involves the constant monitoring for lapses in focus that lead to MW, and practitioners can provide reliable reports of their own MW and meta-awareness events (Lutz, Slagter, Dunne, & Davidson, 2008; Malinowski, 2013). Additionally, FAM involves the focusing of bare attention on a simple stimulus (e.g., sensations of the breath) without cognitively elaborating on any mental contents that arise. Consequently, minimal cognitive resources are likely to be recruited during FAM to maintain task performance. Therefore, the neural activities associated with refocusing attention can be clearly measured and compared to those involved in MW without the interference of other cognitive processes (e.g., counting, responding to external stimuli).

The few studies that have used meditation as a means of investigating MW and focused attention have worked to uncover the time course of interactions between several brain networks. Hasenkamp, Wilson-Mendenhall, Duncan, and Barsalou (2011) were the first to attempt a temporally sensitive examination of the transition from MW to focused attention during FAM using fMRI. Regular meditators were asked to press a button every time they noticed their mind had wandered and then refocus their attention back to their breath during FAM. Because the time sensitivity of fMRI is limited, neural activity was averaged over several three second blocks strategically arranged to capture the four phases hypothesized to be involved in FAM: 1.) MW, 2.) meta-awareness, 3.) shifting attention, and 4.) maintaining focused attention. The first block in the sequence of three second blocks started before the button presses, with the second occurring during the button presses, and the last two blocks following after. Results supported their hypotheses by demonstrating the DMN was most active during the MW block, with robust activations of the PCC and mPFC. Activations in the awareness phase were evident in sensory and motor cortices, and several nodes within the FPCN, which would help participants initiate button presses and engage cognitive control mechanisms. During the phase when attention was shifted from MW to focused attention, increased activations were observed in the lateral PFC and inferior parietal cortex, suggesting executive resources were recruited to deactivate the DMN by decoupling the node shared by the FPCN and the DMN. The focus block was dominated by high activity in the dorsolateral PFC, a central hub of the FPCN that has been repeatedly implicated in studies of focused attention and executive control (Brewer, Worhunsky, Gray, Tang, Weber, & Kober, 2012). The results outlined above support the notion that FAM is an ideal method for inducing MW and attention refocusing.

With a rough outline of the neural networks involved in refocusing attention after a MW episode, further studies have worked to flesh out the effects of FAM on the interactions between networks. In a follow-up study, Hasenkamp and Barsalou (2012) looked at the functional connectivity, measured as the correlation between the activity in different brain networks, in novice and experienced meditators. When compared to new meditators with little experience, expert practitioners displayed increased functional connectivity within the FPCN and between the FPCN and the mPFC. It was suggested that the improved connectivity between the mPFC and FPCN was facilitated by the exercise of repeatedly noticing MW and refocusing attention that is central to the practice of FAM. Additionally, activity in, and connectivity between, areas of the ACC and mPFC were found to have a negative correlation with FAM experience, implying the longer one practices meditation the less effort is required to refocus attention after a MW episode.

Though traditional fMRI analyses are relatively low in temporal resolution, real-time fMRI methodology can facilitate a closer examination of MW-related temporal dynamics. In a series of studies, real-time fMRI methods were used to investigate the role of the PCC in MW generation and suppression during FAM between novice and experienced meditators (Garrison et al., 2013a; 2013b). More specifically, by visually observing feedback of PCC activity on a computer screen in real-time while engaged in FAM, participants could indicate what conscious experiences they had when PCC activity was high or low. As expected, when PCC activity was high, participants reported being distracted and caught up in self-referential MW. Conversely, when PCC activity was low, participants described their experience as clear and focused. Importantly, it was found that regular meditators were better at consciously reducing their PCC activity than were novice meditators, coinciding with an increased ability to stay focused and reduce MW. Furthermore, meditators reported that when they attempted to maintain their focus of attention when their PCC activity was low, it required very little effort on their part to remain focused. On the other hand, novice meditators found it more difficult to stay focused and consciously reduce their PCC activity, reporting a great deal of effort was required to attempt to suppress their MW and maintain low PCC activity. It appears that PCC activity is a good index of how much the DMN is involved in conscious experience, and how focused or distracted a person is at any given moment. Additionally, it may be possible to target PCC activity to investigate how the DMN is deactivated during MW suppression and how interactions between the DMN and other networks are modulated by regular meditation.

Event-Related Spectral Perturbations, Mind Wandering, and Meditation

To verify and build upon fMRI studies that have located the major neural components involved in MW and focused attention, studies have used ERSP analyses to measure the frequency-specific changes in EEG activation during meditation. Cahn, Delorme, and Polich (2013) used an auditory oddball paradigm to compare ERSPs during rest and Vipassana meditation, which is a type of FAM that involves directing attention at physical sensations that arise as one sequentially scans different body parts. When the experienced practitioners were meditating, distractor stimuli evoked decreased delta and alpha activity when compared to the rest condition. With previous studies finding high delta activity being associated with attentional engagement and cognitive elaboration (Basar, Basar-Eroglu, Karakas, & Schurmann, 2001; Ishii et al., 2009), the lower delta power suggested participants were less distractible and better able to suppress stimulus-related MW during meditation. The authors theorized that the decreased alpha activity may indicate a reduced habituation, such that the participant’s attention was free to perceive and quickly disengage from the distractor stimuli. It is also possible that the decreased alpha power may represent the FPCN being recruited to ensure focus was maintained despite the distracting stimuli (Laufs et al., 2003a; 2003b). While adding to our knowledge of the frequency-specific neuronal activation patterns associated with MW and focused attention during meditation, the lack of spatial resolution makes it difficult to associate these ERSP patterns with any particular brain network.

A recent study compared the ERSPs associated with MW and focused attention between a FAM, a BC, an eyes-closed rest, and a SART condition (Fix & Faust, 2017). Button presses in the FAM and BC conditions and commission errors during the SART were all used as behavioral markers for when MW was detected and suppressed to refocus attention (see Figures 1 and 2). The ERSPs surrounding these events were compared to the ERSPs elicited by random button presses during an eyes-closed rest condition, thereby allowing the examination of unique EEG activity patterns associated with MW and focused attention beyond what is required for simple button presses. Directly reproducing the results from a similar study (Braboszcz & Delorme, 2011), button presses in the BC condition were followed by a significant alpha, beta, and gamma ERS and a theta and delta ERD (see Figure 1). Similar ERSPs were observed in the FAM condition (see Figure 2), suggesting these two tasks recruit similar cognitive resources to detect and suppress MW and refocus attention. With such a consistent pattern of ERSPs, it may be possible to investigate the effects of regular meditation practice on the neural network activity associated with refocusing attention after a MW episode. Furthermore, the scalp locations of these ERSPs aligned with major hubs of the FPCN and DMN, indicating it may be possible to use ERSP analyses to directly examine the interactive communication between several brain networks.

EEG and Independent Components Analysis

To increase the spatial sensitivity of EEG measures, a newly developed procedure has been used to locate the independent sources of scalp EEG activity, termed spatial independent component analysis (sICA). Traditionally, EEG activity is detected and analyzed at scalp electrodes (see Figure 4). Investigating EEG activity at the scalp level is problematic, as EEG data at any electrode represents a summation of activity from multiple sources within the brain. On the other hand, sICA allows a source-level analysis by separating the unique activity generated from independent components (ICs) within the brain (Delorme & Makeig, 2004; Onton, Westerfield, Townsend, & Makeig, 2006). By conducting a sICA on EEG data, patterns of activity measured at scalp electrodes can be traced back to their sources within the brain. This is achieved by submitting the EEG time series data from all scalp electrodes, with the 3D location of each electrode, to the sICA which identifies ICs that produce spatially consistent patterns of EEG activity across time (for an example, see Figure 10).

Consider the following example as a conceptual analog to EEG sICA. If microphones were placed around a room which contained a cocktail party, auditory data from each microphone could be used to identify independent sources of all the recorded conversations. Assuming party members stayed in the same spatial location and did not wander around, each microphone would pick up all the words spoken by each person. The words spoken by Person A would be consistently recorded as louder from microphones that were spatially closer, than would microphones positioned farther away. In other words, the amplitude (loudness) of the auditory data associated with Person A recorded at a particular microphone would be positively correlated with the distance between them. This dynamic would be true of all the people talking at the party and would be consistent across time. If the spatial location of each microphone was known, the spatial location of each party member could be estimated by comparing the loudness of their words recorded at different microphones.

In a similar fashion, sICA 1) compares the amplitude of EEG data recorded at each scalp electrode across time, 2) identifies consistent spatial patterns of activity which can be attributed to independent neural source generators (ICs), and then 3) isolates the EEG activity associated with each IC from other EEG activity (see Figures 5, 6, and 10). Theory and empirical studies suggest neural nodes generate electrical activity in the shape of a dipole (Delorme, Palmer, Onton, Oostenveld, & Makeig, 2012), which can be compared in shape with two megaphones that are connected and facing in opposite directions, one expelling a negatively charged signal in one direction, while the other sends a positively charged signal in the opposing direction (see Figure 3). With sophisticated 3D dipole modeling, the scalp maps accompanying each IC can be used to estimate where each sources generator is located within the brain (Delorme, Plamer, Oostenveld, Onton, & Makeig, 2007a). Importantly, the EEG activity associated with each IC that was isolated with sICA can be examined independently of all other EEG activity and can be submitted to further analyses (e.g., ERSP).

With access to ERSPs generated from specific brain sources, it is possible to locate neural nodes associated with different brain networks and compare the activity between spatially independent sources. Recent studies have successfully applied sICA to examine source-localized EEG activity in a variety of contexts, including during rest state (Aoki et al., 2015; Chen et al., 2013; Sockeel, Schwartz, Pelegrini-Issac, & Benali, 2016), 2-back task (Tsai et al., 2006), Stroop Task (Beldzik, Domagalik, Froncisz, & Marek, 2014), social judgements (Knyazev, Slobodskoj-Plusnin, Bocharov, & Pylkova, 2011), and emotion regulation (Ferdek, van Rijn, & Wyczesany, 2016). Furthermore, by correlating the ERSPs generated from different ICs, the functional connectivity between networks can be examined and compared across frequency band, time, and group in a more comprehensive way. Connectivity analyses with EEG data have much greater potential for detecting changes in network communication than is possible with fMRI data (Knyazev et al., 2016). This is because fMRI measures blood flow and not neural activity, while EEG directly measures neural activations and can measure the complex communications across a range of frequency bands, even if a node is simultaneously receiving excitatory and inhibitory signals from other network nodes. With this new technique, studies can take advantage of the temporal sensitivity afforded by EEG recordings without having to make a significant sacrifice in spatial resolution. Unfortunately, sICA analyses are a recent phenomenon and have only been applied to a few cognitive domains and have not been used to investigate MW, focused attention, or meditation (Onton, Westerfield, Townsend, & Makeig, 2006).

The Present Study

A limited number of studies have investigated the interactions between the FPCN, DAN, and DMN during MW, and fewer still have directly measured the activity associated with MW and focused attention during meditation. Advanced neuroimaging techniques like EEG sICA have made it possible to directly measure the activity generated by particular neural networks (Beldzik et al., 2014; Ferdek, van Rijn, & Wyczesany, 2016; Sockeel et al., 2016). By combining the temporal, frequency-specific, and event-related advantages inherent in ERSP analyses with the spatial resolution afforded by sICA, the present study aimed to investigate the interplay between the FPCN, DAN, and DMN that occurred when a MW episode was detected and attention was refocused. The ERSPs generated by specific nodes of each network, identified by sICA, were examined and correlated to the ERSPs from other nodes so that the functional connectivity between networks could be estimated. This functional connectivity analysis indicated when networks were producing synchronized activity and when their activity had been desynchronized. Furthermore, network activity differences were examined between novice meditators and regular meditators to determine if long-term meditation practice alters the interactions between neural networks.

Research Questions (RQ) and Hypotheses

RQ1. Can sICA be applied to EEG data that surrounds the transition from MW to focused attention to identify EEG activity associated with major hubs in the DMN, DAN, and FPCN? Preliminary work has been done to verify the validity of sICA results, and it has been shown that multi-channel EEG recordings can detect subtle changes and group differences in the activity of spatially independent brain sources (Onton et al., 2006). Correlations have also been found between self-referential cognitive processes and the EEG activity of two nodes of the DMN: the PCC and precuneus (Knyazev, Slobodskoj-Plusnin, Bocharov, & Pylkova, 2011).

It was hypothesized that at least one node of the DMN, DAN, and FPCN would be identified so that subsequent analyses could be conducted on neural source activity instead of on electrode activity. Furthermore, it was predicted that the PCC node of the DMN would be easily identified through sICA. With the successful identification of neural network nodes through sICA, the neural network activation and connectivity within and between networks could be estimated and examined more closely than would be possible by examining EEG activity at the level of electrode.

RQ2. Once ICs corresponding to nodes of the three networks have been identified, how will their activity align with previous studies investigating MW during FAM, and what network activity differences will be observed between the novice meditator and regular meditator groups? The picture painted by fMRI data is black and white, such that activity of a specific brain component can only be measured on a single continuum from less to more blood flow. By directly measuring the activity of neural network nodes, along with the addition of frequency information facilitated by EEG ERSP analyses, a more comprehensive examination of network interactions is possible. More specifically, network-specific node activations across the four time epochs (i.e., MW, Aware, Shift, and Focus) surrounding meta-awareness of MW during meditation that were hypothesized to represent pertinent cognitive states in previous studies were compared between EEG data from the present investigation and similar fMRI results (Hasenkamp et al., 2011). Activity associated with nodes of the DMN was predicted to be highest immediately before and lowest during and immediately after the button presses. As found in an earlier study of scalp ERSP changes (Fix & Faust, 2017), DMN suppression was predicted to be observed as a theta and delta band ERD and an alpha, beta, and gamma band ERS. Nodes associated with the FPCN and DAN were hypothesized to be most active during and immediately after button presses, and were predicted to be observed as an alpha, beta, and gamma ERS.

As recent fMRI studies have demonstrated, regular meditators display an enhanced ability to suppress DMN activity (Garrison et al., 2013a; Josipovic, Dinstein, Weber, & Heeger, 2012) and maintain FPCN and DAN activity (Farb, Segal, Mayberg, Bean, McKeon, Fatima, & Anderson, 2007; Froeliger, et al., 2012). As such, it was predicted that DMN deactivations would occur more rapidly and be longer in duration in regular meditators when compared to novice meditators. It was also predicted that the FPCN and DAN activations associated with focused attention would be more robust and persist longer after the button presses for regular meditators relative to novice meditators.

RQ3. Can EEG IC activity be correlated to estimate network communication and how will these estimates compare to functional connectivity results from fMRI studies? The current study attempted to replicate connectivity findings from Hasenkamp and Barselou (2012) by correlating ERSP activity between network nodes within the DMN, FPCN, and DAN in each traditional EEG frequency band. It was predicted that a similar sequence of connectivity changes would be observed as participants noticed their MW and returned to focused attention, with FPCN and DMN functional connectivity increasing when MW must be suppressed (e.g., before button presses), and FPCN and DAN functional connectivity increasing when attention is shifted and focus must be maintained (i.e., during and after the button press). Furthermore, functional connectivity was predicted to differ between groups, such that meditators would display greater connectivity between the FPCN and DMN, representing their enhanced ability to disengage and suppress MW.

CHAPTER 2: METHODS

Participants

Regular meditators were recruited in person from a medium-sized Mid-Atlantic university and from local meditation groups within the surrounding area, while meditation-naive participants were recruited from introductory psychology courses via an online recruitment website maintained by the university. Inclusion criteria were that participants were right handed with normal or corrected vision, were fluent English speakers, and had either no meditation experience or had maintained a regular meditation practice (> three times weekly) for at least one month. Left-handers, people with visual impairments that could not be corrected with contacts, and non-English speakers were excluded from the study. Twenty-two regular meditators and 24 meditation-naive control participants were recruited to run through the experiment. Upon completion of the experiment, participants were offered 2.5 hours of psychology class research credit and two $10 Target gift cards.

Materials

The paper surveys included a novel demographic survey with a few questions regarding meditation experience, a handedness and general health survey, the Five Facet Mindfulness Questionnaire (Baer et al., 2008), and the Perceived Stress Scale (Cohen et al., 1983). The Five Facet Mindfulness Questionnaire has been validated in several studies, showing appropriate factor loadings for five factors in factor analysis, strong internal consistency on all five factors and the total score (Cronbach's alpha > .70), and adequate convergent and divergent validity with high correlations with expected subscales from the Trait Meta-Mood Scale and the Satisfaction with Life Scale (Christopher, Christopher, & Charoensuk, 2009; Christopher, Neuser, Michael, & Baitmangalkar, 2012). The Perceived Stress Scale has also been well validated, with one review article observing adequate values for internal consistency (Cronbach's alpha > .70) and test-retest reliability (Pearson's r > .70), while also reporting strong criterion validity with high correlations to the mental factor on the Short Form 36 (Lee, 2012).

Procedure

A between-groups cross-sectional design was used to examine EEG differences between regular meditators and novice meditators while participants engaged in FAM. After recruitment, participants were brought into the research laboratory, written informed consent was obtained, paper surveys were administered, and then a FAM was taught so that all participants would practice the same type of meditation. The current study utilized a similar training protocol to other studies of brief meditation interventions (e.g., Zeidan, Johnson, Diamond, David, & Goolkasian, 2010). The FAM taught to all participants involved sitting comfortably with eyes closed, observing the sensations of the breath as it entered and left the nose, noticing when the mind had wandered away from the breath, and returning the focus of attention back to the breath after the MW episode had been detected.

After participants had been trained in the FAM, they were given an instructional handout that described the FAM and the procedure for practicing at home while logged into a secure website. Each participant was required to go home and practice the FAM three times for fifteen minutes while logged onto our website that tracked each time they pressed a button to indicate they noticed their mind had wandered away from their breath. When the three home meditation sessions had been completed, the participants returned to the lab for the EEG testing session. Participants were hooked up to a 64-channel Neuroscan EEG system and underwent a procedure which counterbalanced four experimental conditions.

EEG Recording

A Neuroscan 64 channel SynAmps2 amplifier recorded continuous EEG data from a 64 channel Quikcap that utilized an extended 10-20 system of electrode placement (see Figure 5). Electrode caps were filled with electroconductive gel to ensure relatively low (<10KOhm) impedance levels between the electrode and the scalp. All scalp electrodes were referenced to an additional electrode that was located between the Cz and CPz electrodes. One electrode was place above and below the left eye and on either temple to measure eye movements, along with one electrode on each mastoid as backup reference channels. Data were recorded with a sampling rate of 1000 Hz.

Data Processing

A processing and analysis pipeline similar that used in recent studies (e.g., Ferdek, 2016) was conducted to address the current research questions (see Figure 10). The following steps were used on each participants data: 1.) data was visually inspected and artifactual sections of continuous data were removed, 2.) bad electrodes were removed, 3.) data was downsampled to 256k Hz, 4.) low- and high-pass filters at .1 and 55 Hz were applied, 5) data was epoched to 20 seconds surrounding button presses, 6.) bad epochs were removed, 7.) sICA was performed, 8.) a dipole source model was fit to each IC, 9.) bad ICs were identified, 10.) eyeblink and muscle ICs were removed from the data, 11.) ERSPs were generated for each IC, 12.) all valid ICs were clustered according to ERSPs and dipole locations, 13.) ERSPs were calculated for each cluster and target electrode 14a.) ERSP data was reduced to averages within each frequency and time epoch window for activation analyses, 14b.) averaged correlations were calculated between target electrode pair ERSPs for connectivity analyses, and 15.) separate 2 X 2 Analysis of Variance (ANOVA) tests were conducted.

Data were exported from the Neuroscan software to the EEGLAB 13 (Delorme & Makeig, 2004) toolbox for Matlab 2014a (The Mathworks, Inc.). Continuous data were visually inspected so that sections with large amplitude non-stereotyped artifacts can be removed. Individual electrodes with extreme values (+- 100uV), improbable (> 5*SDs*) data, and abnormally distributed (> 5*SDs*) data were identified and removed with a semi-automated protocol implemented in EEGLAB (Delorme, Sejnowski, & Makeig, 2007). Continuous data were downsampled from 1000 to 256 Hz, high-pass filtered at .1 Hz and low-pass filtered at 55 Hz to remove baseline drift and ambient electrical noise. Each participant’s continuous data were segmented into 20 second epochs that surrounded button presses. Epochs were evaluated by a semi-automated procedure within EEGLAB to identify and remove epochs that contain extreme values (+- 50uV), improbable (> 4 *SDs*) data, and abnormally distributed (> 4 *SDs*) data.

Source Localization with Spatial Independent Component Analysis

A standardized source localization procedure, adopted from the work of Onton and colleagues (2006), was used on individual- and group-level data (see Figure 10). Epoched EEG data recorded at scalp electrodes from each participant were subjected to an Infomax sICA to identify spatially independent components that generated the observed scalp EEG activity patterns. The DIPFIT2 plugin for EEGLAB was used for dipole source modeling to localize each IC in 3D space based on a standardized boundary element head model, for each participant (Delorme et al., 2007a). All ICs were visually inspected to identify and remove those that were located outside the skull based on the position of the IC's dipole relative to a 3D boundary element head model, along with those ICs that displayed less than 15% residual variance of the dipole location (Wyczesany, Grzybowski, & Kaiser, 2015). Additionally, the ICs involved in the generation of artifacts like eye blinks, lateral eye movements, and other facial muscle activity were identified and removed by comparing the scalp map for each IC to scalp map templates of these common EEG artifacts (Mennes, Wouters, Vanrumste, Lagae, & Stiers, 2010).

After ICs were calculated for each participant, ERSPs were generated for each clean IC and then ICs were clustered across participants to facilitate further analyses of neural network node activations. Evaluating independent component clustering methods has become a topic of interest in neuroscience research (Delorme, Palmer, Onton, Oostenveld, & Makeig, 2012), though no method has emerged as optimal across all applications. A k-means clustering technique, like that used by Lenartowicz and colleagues (2013), was implemented to group ICs together across subjects, equally prioritizing a match based on 3D dipole source locations and the ERSPs generated for each IC. Similar to Ferdek et al. (2016) and Jung et al. (2007), and iterative process was conducted, starting at k = 20 and reducing by one, which aimed to find the optimal clustering solution that minimized the merging of apparently separate clusters. The analysis resulted in 19 IC clusters (see Figure 7) which were used in all subsequent neural network node activations. Table 2 depicts the number of ICs present in each of the 19 clusters.

EEG Time-Frequency Analysis

After all data preprocessing was complete, clean epochs were averaged within each group and a Morlet wavelet decomposition was conducted to display EEG data from 1 Hz to 50 Hz into 200 linearly-spaced time points in a time-frequency matrix for each channel and IC. Wavelet decomposition differs from the more traditional Fourier transform in that the later only uses a one Gaussian waveform kernel (Cohen, 2014). The wavelet kernels chosen for the present study had 3 cycles each, with one small, one large, and one small Gaussian waveform (each with the same width as would be appropriate for the given frequency) connected in that order. Wavelet decomposition iteratively takes these wavelet kernels and passes them along the time series data to detect oscillatory activity matching that wavelet shape within the EEG data. Wavelet decomposition produces a time series of data for each frequency specified which are then stacked on top of each other to make the time-frequency map (as depicted in Figures 1 and 2).

Data preprocessing and preparation for IC correlation analysis revealed very few participants had both ICs necessary for the proposed IC-based connectivity analyses. As such, the individual EEG electrode that was directly above each IC was identified with IC scalp maps and used for further connectivity analyses. Correlations were made between ERSPs generated at each target channel (each representing an IC) so that network functional connectivity could be examined. Periods of highly correlated activity between channels representing nodes of different networks were indicative of high functional connectivity and synchronized activity.

Data Reduction and Analysis

To reduce the need for conservative multiple comparisons corrections, and to maximize the potential to reproduce the effects observed in two studies of meditators neural network node activity (Hasenkamp et al., 2011) and connectivity (Hasenkamp & Barsalou, 2012), EEG activity and connectivity within each frequency band and time epoch was averaged together (see Figure 11) to conduct separate 2 X 2 mixed factorial ANOVAs in a similar fashion to other ERSP connectivity studies (e..g., Ferdek et al., 2016). For neural network node activity analyses, the average ERSPs generated by each participant's IC that contributed to a cluster were reduced to the average activity within each frequency band (delta <1-4 Hz, theta 4–7 Hz, alpha 8–13 Hz, beta 12-30 Hz, gamma 30-45 Hz) for each time epoch. The time epochs used in the present study perfectly mirrored the four time epochs used by Hasenkamp and colleagues (2011), which were arranged relative to the button presses signifying MW meta-awareness during meditation (see Figure 11). Activity within each of the five frequency bands from the cluster ERSPs was averaged within the time epochs of MW (-5 to -2 s), Aware (-2 to 1 s), Shift (1 to 4 s), and Focus (4 to 7 s).

Connectivity analyses were conducted in a similar fashion to the activity analyses described above, with a few notable exceptions. First, channel ERSPs were used instead of those generated by clusters, as an inadequate amount of cluster pairs were available for connectivity analyses. Second, instead of averaging the activity within a frequency band and time epoch window, the time-series of activity occurring within each frequency band

and time epoch window was correlated between two target electrodes. For each frequency band and time epoch window, a correlation value was produced which measured the average connectivity across time between the electrode pair within that window. These electrode pair correlations represent an estimate of the average connectivity between the neural network nodes which are closely situated to the target electrodes.

All activation and connectivity analyses followed the same statistical procedure. After activation and correlation averaged values were computed for each participant for each window, a 2 X 2 mixed factorial ANOVA was conducted to compare MW to the other three time epochs in a similar fashion to the two studies the current investigation aimed to replicate (Hasenkamp & Barsalou, 2012; Hasenkamp et al., 2011). The following result are reported in terms of main effects of time and group, along with interaction effects between these main effects. It should be noted that each statistical comparison reported below represents a difference between MW and one of the other time epochs: Aware, Shift, or Focus. Planned comparisons were conducted for each significant result found in the two studies being replicated, along with additional exploratory analyses outside of these targeted windows.

CHAPTER 3: RESULTS

The participant's ages varied considerably within both groups, ranging from 18 to 54 years (M = 23.0, SD = 9.5) in the novice meditator group and 19 to 71 years (M = 33.3, SD = 17.1) in the meditation group, though there was no significant age difference between the two groups. The final analysis contained a novice meditator group with 24 total participants (17 females) and a regular meditator group with 22 total participants (8 females). The following results were produced by a processing pipeline (see Figure 10) which has been validated across several studies (Aoki et al., 2015; Beldzik et al., 2014; Ferdek et al., 2016; Sockeel et al., 2016; Tsai et al., 2006). Similar to these studies, the following processing steps were conducted on EEG data collected from 64 electrodes: 1.) data was visually inspected and artifactual sections of continuous data were removed, 2.) bad electrodes were removed, 3.) data was down sampled to 256k Hz, 4.) low- and high-pass filters at .1 and 55 Hz were applied, 5) data was epoched to 20 seconds surrounding button presses, 6.) bad epochs were removed, 7.) sICA was performed, 8.) a dipole source model was fit to each IC, 9.) bad ICs were identified, 10.) eyeblink and muscle ICs were removed from the data, 11.) ERSPs were generated for each IC, 12.) all valid ICs were clustered according to ERSPs and dipole locations, 13.) ERSPs were calculated for each cluster and target electrode 14a.) ERSP data was reduced to averages within each frequency and time epoch window for activation analyses, 14b.) averaged correlations were calculated between target electrode pair ERSPs for connectivity analyses, and 15.) separate 2 X 2 ANOVAs were conducted.

RQ1: sICA and Dipole Source Localization.

The first aim of the present study was to evaluate whether sICA could be used to identify and isolate the EEG activity associated with individual nodes in the DMN, DAN, and FPCN. After individual-level sICA was performed for each participant on EEG data from 64 electrodes, ICs were clustered across participants to create nineteen maximally independent clusters. Cluster scalp maps and dipole locations for all nineteen clusters are displayed in Table 1 and Figure 5 and Figure 6 respectively. The k-means clustering algorithm separated three outlier clusters, each which contained very few ICs (< 4). Coordinates within Montreal Neurological Institute (MNI) space, which is a standardized metric used across neuroimaging modalities, were calculated for the centroid of the remaining sixteen clusters (see Table 1), and each cluster was visually matched to the nearest Brodman's Area. Additionally, standard deviations and standard errors were calculated for each cluster to estimate the spatial density of each cluster, which is an average of all the distances from each IC to the cluster centroid. As can be seen in Table 1, most of the clusters used in the present analyses had consistent densities, suggesting a similar amount of confidence can be applied to the results from these clusters. On the other hand, results from clusters with relatively larger estimates of density (e.g., the left AI cluster), indicating low density of ICs contributing to that cluster, should be viewed more cautiously.

Several clusters were estimated to represent nodes of the three neural networks under study, while matching other clusters to appropriate Brodman's Areas was not as straight forward. Due to individual differences in cortex gyration, the inherently low spatial resolution of sICA-based EEG source localization, and the lack of objective methods for evaluating source localization results, cluster-to-Brodmans's-Area-matches reported in the present investigation should be viewed as tentative. A cluster was matched to both the left and right PCC, right and left posterior parietal cortex (PPC), and the ventral medial PFC, all of which are nodes of the DMN (see Figure 7). The FPCN was represented by a cluster in the dorsal ACC, and right and left inferior parietal cortex (see Figure 8). The DAN was represented by a cluster in the posterior section of the ACC, along with clusters located at the right and left anterior insula and primary sensory and motor cortices (see Figure 9).

The above results support the hypothesis that sICA and dipole source localization can successfully identify individual nodes of the three target neural networks within EEG data. The present findings represent a small advancement for the field of MW research as no study to date has identified clusters within all three networks, nor has any study presented dipole density findings from an EEG sICA. Although it appears the identified clusters match several nodes within the three networks, all sICA-based results in the current investigation should be taken with significant caution as more sICA validation studies, along with formal methods for evaluating the goodness of fit (e.g., dipole density) for a sICA solution, are needed.

RQ2: Replicating fMRI Results with EEG sICA Activations.

The second aim of the present investigation was to replicate neural network activations found in meditators by Hasenkamp and colleagues (2011), and to compare these activations to those produced by novice meditator control participants. To accomplish this goal, ERSPs generated by IC clusters were compared between regular meditator and novice meditator participants across the four time epochs used by

Hasenkamp and colleagues (2011). For the following results (see Figure 11), MW will refer to the epoch 5 to 2 seconds before participants pressed the button to indicate they had noticed their mind had wandered away from their breath. The Aware epoch started 2 seconds before the button press and ended 1 second after. The Shift epoch goes from 1 to 4 seconds, and the Focus epoch is 4 to 7 seconds, after the button press. Within each epoch, the neural network nodes found to display significantly increased BOLD activity in the original study were examined for changes in EEG activity across the five traditional frequency bands (delta < 4 Hz, theta 4–7 Hz, alpha 8–12 Hz, beta 12-30 Hz, Gamma 30-55Hz; Pfurtscheller & Lopes da Silva, 1999). Activations during the Aware, Shift, and Focus epochs were compared to activity in the MW epoch with separate 2 (group) X 2 (epoch) mixed factorial ANOVA tests. A Bonferroni Correction was applied to each replication ANOVA to control for Type 1 error, which moved the p-value significance threshold to .01 for individual frequency-band-specific tests. Exploratory results outside of the planned replication windows are presented with uncorrected significance values.

Comparing Aware to MW. The present study found significantly increased activity during the Aware epoch in three neural network nodes (see Tables 2,3, and 4) that displayed significant BOLD increases in the original study (Hasenkamp et al., 2011). Most notably, meditators displayed significantly lower overall ACC delta activity and a larger decrease from MW to Aware that produced a significant main effect of group $F(1, 81) = 8.19$, $p = .005$ and a marginally significant interaction effect ($p = .038$). Theta band activity decreased from MW to Aware for both groups in a significant main effect of time $F(1, 81) = 8.61$, $p = .004$, and a main effect of group ($p = .03$) which approached significance demonstrated meditators had an overall lower theta across epochs. Meditators displayed a marginally significant interaction effect increase in Alpha from MW to Aware when compared to novice meditator participants. There also was a main effect of time showing an increase in beta $F(1, 81) = 15.06$, $p < .001$ and gamma $F(1, 81) = 22.04$, $p < .001$ activity for both groups, as well as a marginally significant main effect of group in the gamma band.

Along with the significant effects in the ACC, clusters in the left anterior insula and primary somatosensory and motor cortices produced activity changes which replicated findings from the original study. Results show a significant beta $F(1, 53) = 7.29$, $p < .009$ activity increase and a trending-towards-significant gamma activity increase in the left anterior insula between MW and Aware in both meditators and novice meditators, replicating the findings from Hasenkamp and colleagues (2011). Both groups displayed several marginally significant changes in activity from the cluster located at the left primary somatosensory and motor cortices between MW and Aware, with theta activity decreasing and alpha, beta, and gamma activity increasing.

Exploratory analyses revealed that most of the significant effects found for the ACC, left AI, and left M1 clusters during the targeted comparisons between MW and Aware continued into the later Shift and Focus epochs. The pattern of decreased ACC delta and theta coupled with increased beta and gamma was also observed in the MW and Shift comparison, suggesting both groups were utilizing their FPCN to disengage from MW and shift focus back to the breath. Additionally, small group effects were found which indicated regular meditators had reduced their ACC activity during the Focus epoch in the alpha and gamma bands, while novice meditator participants had not. A main effect of group and interaction effect were detected, such that only regular meditators maintained the reduced theta activity during the Focus epoch that was observed for both groups in the Aware and Shift epochs. Significant beta band increases were preserved, as well as an additional increase in alpha activity, for both groups in the left AI cluster during Shift and Focus. Furthermore, the changes in left M1 activity observed during Aware continued into the Shift and Focus epochs for both groups.

Comparing Shift to MW. The two neural network nodes that displayed significantly altered BOLD activity during the Shift epoch in the Hasenkamp et al. (2011) study also exhibited detectable changes in the present investigation (see Tables 2,3, and 4). The cluster identified as the right dlPFC had increased beta activity ($p < .043$) which trended towards significance in both groups. Clusters in both the left and right inferior parietal cortices (IPC) had significant changes in activity between MW and Shift as well. The left IPC produced main effects of time in several frequency bands, with a marginally significant decrease in delta activity ($p = .018$) and increases in alpha ($p = .013$), beta $F(1, 61) = 15.32$, $p < .001$, and gamma activity ($p = .048$) between MW and Shift. The right IPC displayed the same exact pattern of results as the left IPC, with significant main effects of time evident in the decreased delta $F(1, 71) = 7.38$, $p = .008$ and increased alpha $F(1, 71) = 13.14$, $p < .001$, beta $F(1, 71) = 12.98$, $p < .001$, and marginally for gamma ($p = .018$) between MW and Shift. Additionally, a marginally significant decrease in theta activity was found in both groups.

Outside of the targeted MW to Shift comparisons, exploratory analyses detected several other significant effects in the FPCN between MW and Shift. Right IPC main effects of time in the alpha, beta, and gamma bands spanned all three time epochs, as did the beta increases detected in the left IPC. The significant increase found for left IPC alpha activity in the Shift epoch began as an increase in the Aware epoch, and the delta decrease observed during Shift extended after that epoch into the Focus phase for both groups.

Comparing Focus to MW. The only neural network node that had significantly altered BOLD activity in the comparison study (Hasenkamp et al., 2011) did not display a significant effect in the current study (see Table 4). The right dlPFC cluster produced a marginally significant main effect of time in the beta band and an interaction effect in the alpha band. Though these effects had large effect sizes, the power for these tests was relatively low because of the small number of participants who had ICs in this cluster.

Comparing MW to Shift. The current study aimed to replicate the remaining comparisons made by Hasenkamp and colleagues (2011) by contrasting DMN node activations in the MW and Shift epochs (see Table 4). The cluster in the left PCC produced significant main effects of time in several frequency bands, with higher alpha $F(1, 81) = 12.13$, $p < .001$, beta $F(1, 81) = 26.25$, $p < .001$, and gamma $F(1, 81) = 12.34$, $p < .001$ activity being detected in the Shift epoch compared to MW. The right PCC cluster displayed the same pattern of time main effects, with higher alpha $F(1, 97) = 8.1$, $p = .005$, beta $F(1, 97) = 14.0$, $p < .001$, and gamma $F(1, 97) = 9.68$, $p = .003$ band activity being produced in the Shift epoch. Additionally, the right PCC cluster had a marginally significant main effect of time and interaction effect in the theta band, with regular meditators exhibiting a larger decrease in theta activity from MW to Shift.

Significant effects were observed in the present investigation in two other nodes of the DMN, the right and left posterior parietal cortices (PPC). A main effect of time was significant in the left PPC in the alpha $F(1, 77) = 9.74$, $p = .003$, and beta $F(1, 77) = 7.87$, $p = .006$ bands, and marginally in the gamma ($p = .040$) band, with both groups producing significant increases in activity in all three frequency bands during the Shift epoch. A main effect of time was also significant in the right PPC in the alpha $F(1, 91) = 8.90$, $p = .003$ and beta $F(1, 91) = 13.07$, $p < .001$ frequency bands.

The last neural network node examined in the present study and in the original study was the ventral-medial prefrontal cortex (vmPFC), a major hub of the DMN. Within the vmPFC, a main effect of time was detected such that both groups displayed higher alpha ($p = .032$), beta $F(1, 59) = 10.63$, $p = .002$, and gamma ($p = .040$) activity during the Shift epoch than when MW.

Beyond the planned comparisons between MW and Shift, nodes of the of DMN displayed noteworthy changes in activity during other time epochs. The significant alpha, beta, and gamma increases observed for both the right and left PCC during Shift were also found in the Aware and Focus phases in the left PCC only. Additionally, a marginally significant main effect of group and interaction effect in left PCC activity showed that regular meditators had a larger jump in alpha activity between MW and Aware than did novice meditator participants, along with a similar alpha interaction effect in the vmPFC. Regular meditators also exhibited lower overall gamma activity during the Aware epoch in both the right and left PPC and a larger decrease in gamma activity on the right side. This gamma decrease in regular meditators during Aware coincided with a main effect increase in beta activity for both groups which continued, along with an increase in alpha activity, into the Focus epoch. The increased vmPFC beta activity found in the Shift epoch was mirrored both during Aware and Focus.

RQ3: Replicating fMRI Connectivity Results.

A follow-up study conducted by Hasenkamp and Barselou (2012) reported the connectivity analyses associated with their original study. The present study examined each neural network node pair found to display significant BOLD correlations in the previous study. Although the present study planned to examine correlations between IC-derived ERSP activity, the low number of participants (often <10) that had ICs for both neural network nodes within each analysis pair made this strategy inappropriate. Alternatively, the current investigation used a more standard approach to EEG connectivity analyses by using representative electrode channel activity for each IC (Miskovic & Schmidt, 2010; Siems, Pape, Hipp, & Siegel, 2016; van Diessen et al., 2015 Yuvaraj e al., 2016). Scalp maps were visually examined and the electrode within the center of activation for each IC was chosen to represent that particular IC. Table &&& depicts the dipole location and scalp map, along with the representative channel highlighted, for each IC included in all three research questions. It should be noted that throughout the following connectivity results, neural network node names will be used even though the analysis was between electrodes chosen to stand in for each IC.

Connectivity with the FPCN during Aware. The original study (Hasenkamp & Barsalou, 2012) found several network nodes significantly correlated to the dACC, a shared node between the FPCN and DAN, during the Aware epoch. Significant increases in connectivity between the left IPC, a part of the FPCN, and the dACC were observed for both groups in the beta frequency band $F(1, 91) = 41.62$, $p < .001$, and marginally in the gamma band, when comparing MW to the Aware epoch (see Table 5). Additionally, a marginally significant interaction effect in alpha connectivity was observed for the dACC and left IPC pair between MW and Aware (*p* = .044), as the novice meditator group displayed increasing, and the regular meditators had decreasing, connectivity.

The present study found several connectivity differences between the MW and Aware epochs for the dACC and a spot more posterior within the mid-cingulate (see Table 8) that is often associated with DAN activity (Anticevic et al., 2012). Significant main effects of time were observed as increased alpha *F*(1, 91) = 8.71, *p* = .004, beta F(1, 91) = 30.20, *p* < .001, and gamma *F*(1, 91) = 10.23, *p* = .002 frequency band connectivity for this network node pair. Furthermore, regular meditators generated lower overall connectivity between the dACC and mid cingulate in the alpha (*p* = .024) and gamma (*p* = .013) frequency bands when the MW and Aware epochs were compared.

Another interaction between the FPCN and DAN was investigated with the dACC and left primary sensorimotor cortex (M1). In a similar fashion to other connectivity findings between the MW and Aware epochs, main effects of time were observed as increased correlated alpha (*p* = .014), beta (1, 91) = 34.86, *p* < .001, and gamma (*p* = .043) activity (see Table 8). Moreover, novice meditator participants had higher gamma connectivity (*p* = .038) in both conditions compared to regular meditators.

The last connectivity pair hypothesized to have differences between the MW and Aware epochs was between the dACC and a node of the DMN, the right PPC. A marginally significant main effect of time was evident in the beta (*p* = .016) and gamma band, with both groups increasing connectivity between MW and Aware (see Table 10). Two additional marginally significant results were found for this node pair: a main effect of group which showed regular meditators had lower overall alpha connectivity, and an interaction effect with theta connectivity decreasing for novice meditator participants and increasing for regular meditators.

Overall, results comparing FPCN connectivity between the MW and Aware epochs revealed increased correlated activity both within and between networks in both groups. Increased connectivity with the FPCN was most apparent in the beta band, followed by gamma and alpha activity. Several of these main effects continued into the Shift and Focus epochs, especially in the beta band, suggesting increased high frequency connectivity is associated with mental engagement and effort. In further support of this notion, several main effects of group and interaction effects were observed such that regular meditators displayed lower connectivity both within and between the FPCN and other networks. Generally, results from the above comparisons did not replicate the group connectivity differences found by Hasenkamp and Barsalou (2012), as the relatively few main effects of group and interaction effects showed regular meditators had lower (instead of higher) connectivity than novice meditator participants in most instances. Two notable exceptions were the replicated lower connectivity in regular meditators between the dACC and left M1 in the gamma frequency band and in the alpha band between the dACC and right PPC.

Connectivity with the FPCN during Shift. In the Hasenkamp and Barsalou (2012) study, two nodes from the FPCN displayed significant BOLD correlations with other network nodes during the Shift epoch. The present investigation attempted to replicate the above results with correlations between the right dlPFC or right IPC and another FPCN node (left dlPFC) and a DMN node (right PPC). The first connectivity comparisons were all within the FPCN (see Table 5). Between the left and right dlPFC, both groups displayed a marginally significant decrease in theta band connectivity from MW to Shift, and the novice meditator participants generated marginally higher connectivity overall in the delta (p = .022), as well as in the theta and gamma, band than did regular meditators. A significant main effect of group was observed between the left and right dlPFC in the Focus epoch as well, though contrary to findings from the Hasenkamp and Barsalou (2012) study, regular meditators had lower overall connectivity when compared to novice meditators that reached significance in the theta (p = .016) band and trended towards significance in the alpha band. Again comparing connectivity between the MW to Shift epochs, regular meditators had significantly lower overall alpha $F(1, 91) = 7.58$, $p = .007$ and gamma $F(1, 91) = 7.52$, $p = .007$ synchrony for the right IPC and left dlPFC pair.

Connectivity between the FPCN and DMN was calculated as the correlation between either the right dlPFC or right IPC and the right PPC (see Table 10). A marginally significant beta (p = .049) and gamma main effect of time was observed for the dACC and right PPC node pair as both groups increased connectivity from MW to the Shift epoch. A marginally significant main effect of group was also observed, with regular meditators showing a higher overall alpha connectivity than did novice meditator participants. Regular meditators also had a small decrease in theta correlated activity between these node pairs during the Aware phase, while novice meditator participants displayed a decrease in connectivity. Another comparison which measured connectivity between the FPCN and DMN was between the right IPC and right PPC. Both groups generated a significant increase in alpha connectivity $F(1, 91) = 9.20$, $p = .003$ between MW and Shift. Additionally, novice meditator participants displayed marginally higher beta and significantly higher gamma correlated activity *F*(1, 91) = 8.99, *p* = .003 between these network nodes.

Results from the MW and Shift FPCN comparisons run in direct contradiction to those reported by Hasenkamp and Barsalou (2012), as the present study found that regular meditators had less correlated activity within the FPCN and between the cognitive novice meditator network and the DMN. For time periods outside of the hypothesized windows, this pattern of results was also observed for the MW and Aware comparisons, and to a lesser extent in the MW and Focus comparisons (see Tables 5 through 10). Additionally, main effects of time were apparent when comparing MW to the Aware epoch in all four network node pairs, such that both groups generated a significant increase in beta and gamma connectivity.

Connectivity with the DMN Comparing MW and Shift. To investigate connectivity pattern during MW, three of the main hubs of the DMN, the vmPFC and bilateral PCC, were targeted with comparisons between MW and the epoch hypothesized to be most unlike MW, the Shift epoch. These within-network node pairs, along with several planned between-network pairs with nodes from the FPCN and DAN, were examined to replicate connectivity findings from the Hasenkamp and Barsalou (2012) study. Results show no significant connectivity differences within the DMN between the vmPFC and left PCC when comparing the MW and Shift epochs (see Table 7). Several marginally significant differences in connectivity were found between the vmPFC and right PCC, with MW being associated with higher theta and lower beta and gamma connectivity in both groups, and regular meditators displaying higher overall theta connectivity in both conditions.

Connectivity differences were found between MW and Shift for the vmPFC and one node of the DAN (see Table 9) and five nodes within the FPCN (see Table 10). Main effects of time were observed for the vmPFC and left M1 pair as both groups had reduced theta (*p* = .026) and increased beta *F*(1, 91) = 6.95, *p* = .010 and gamma (p = .037) connectivity. For the between-network vmPFC and dACC pair, the present investigation found a main effect of time such that both groups had lower beta correlations (*p* = .050) during MW when compared to the Shift epoch. Additionally, regular meditators displayed overall higher theta correlations in vmPFC and dACC activity during both MW and Shift for a marginally significant main effect of group (p = .015). For the left PCC and dACC pair, a main effect of group (*p* = .023) was observed as regular meditators had overall lower gamma connectivity in both MW and Shift epochs. Furthermore, a marginally significant interaction effect was apparent between these DMN and FPCN hubs, as novice meditator participants exhibited an increase in gamma connectivity from MW to Shift that the regular meditators did not. During the MW epoch, both groups displayed marginally significantly lower beta and significantly lower gamma *F*(1, 91) = 8.73, *p* = .004 connectivity between the right PCC and dACC when compared to the Shift epoch. Furthermore, regular meditators had marginally significantly lower overall gamma connectivity between these DMN and FPCN hubs in both MW and Shift epochs.

Activity correlations were also compared between the MW and Shift epochs for the vmPFC and four other nodes of the FPCN (see Table 10). Two marginally significant connectivity differences were observed for the vmPFC and left IPC pair: both groups displayed increased beta connectivity, and an interaction effect was evident as alpha connectivity increased for novice meditator participants and decreased for regular meditators. In a similar pattern, the vmPFC and right IPC pair was associated with a marginally significant increase in beta correlated activity in both groups between MW and shift, and regular meditators generated lower overall gamma compared to novice meditator participants. The present investigation failed to replicate the correlation differences in BOLD activity for the vmPFC and left dlPFC between MW and Shift that were reported in the Hasenkamp and Barsalou (2012) study. However, correlation differences were observed for the vmPFC and right dlPFC pair between MW and Shift, with both groups displaying a significant increase in beta connectivity $F(1, 91) = 9.20$, $p = .003$ and an increase in alpha activity which trended towards significance.

Beyond the planned replication comparisons in DMN connectivity between the MW and Shift epochs, every network node pair displayed significantly different connectivity between MW and the earlier Aware epoch. A main effect of time was observed in the beta frequency band for all five examined comparisons. A similar pattern of results was apparent in the alpha and gamma frequency bands, as main effects of time were observed for most of the five connectivity pairs when comparing MW and Aware. Main effects of group were observed for several network node pairs, with regular meditators generally displaying lower overall connectivity compared to novice meditators in one or more frequency band. Along with the planned connectivity comparisons outlined above, these findings suggest MW is associated with a broad reduction in alpha, beta, and gamma connectivity within and between each neural network. Very few significant results were found when comparing connectivity between the MW and Focus epochs among these node pairs.

Connectivity with the FPCN during Focus. Nodes of the FPCN did not display correlated activity differences between the MW and Focus epochs with the two network nodes predicted in the current study. Both groups did display a marginally significant increase in delta correlated activity between MW and Focus, and regular meditators had marginally lower overall gamma connectivity, for the right dlPFC and right AI pair (see Table 8). Although the present investigation failed to replicate the connectivity differences between MW and Focus found by Hasenkamp and Barsalou (2012), the right dlPFC did have several correlated activity differences in other epoch pairs. Between the MW and Aware epochs, both groups generated significant increases in delta, alpha, beta, and gamma correlated activity for the network node pairs including the right dlPFC and either node of the DAN: the right AI or mid-cingulate. Additionally, regular meditators had lower overall gamma connectivity for both node pairs and lower alpha connectivity within the right dlPFC and mid-cingulate pair. Furthermore, the gamma band main effect of time between both pairs of nodes, and the right dlPFC and right AI pair delta band main effect of time, continued into the MW and Shift comparison. Additionally, regular meditators had lower overall gamma correlated activity for the right dlPFC and right AI pair when MW and Shift were compared.

CHAPTER 4: DISCUSSION

Meditation practices from a variety of contemplative traditions have been used for centuries to improve attention stability, reduce superfluous mental activity, and enhance well-being. Many researchers in the scientific community have begun to evaluate the efficacy of different meditative techniques on a wide range of outcome measures. Attention stability has become an early target for the scientific study of meditation, and several studies have investigated the neural mechanisms behind meditators' ability to stave off mind wandering and remain focused. The present investigation used EEG data to replicate findings from recent studies that examined the time course of neural network interactions surrounding participants' awareness of their MW. Regular meditators and participants without meditation experience were trained in a simple FA meditation technique that has been found to reduce MW incidences (Vago & Zeidan, 2016; Zanesco et al., 2016). During three training sessions and the EEG testing session, participants engaged in FA meditation and pressed a button every time they noticed their mind had wandered away from the sensations of their breath. Event-related spectral perturbations from sICA-derived neural network nodes, along with network connectivity alterations between representative electrodes, were measured and compared to estimate the changes in brain activity associated with four time epochs: MW, awareness of MW, disengagement from MW and shifting attention, and sustained focused attention.

Electroencephalographic data associated with individual nodes of the FPCN, DAN, and DMN were successfully isolated and compared using sICA and dipole clustering (see Figure 10). Both groups displayed significant changes in EEG oscillatory activity and connectivity over time that mirrored results found in previous EEG (Braboszcz, & Delorme, 2011; Fix & Faust, 2017) and fMRI studies (Hasenkamp et al., 2011; Hasenkamp & Barsalou, 2012). Surprisingly few group differences were observed in EEG activation changes, and most of the connectivity differences between regular meditators and novice meditators were found to be contradictory to previously reported BOLD connectivity results. Findings from the current study provide preliminary support for the use of sICA to isolate EEG data generated by unique neural network nodes.

sICA Source Localization

The present study is just one example from a growing field which aims to develop, evaluate, and apply source localization methods to EEG data. While traditionally low in spatial resolution, several EEG source localization methods have demonstrated relatively consistent performance across studies (Siebenhühner, Lobier, Wang, Palva, & Palva, 2016; Sadaghiani, Scheeringa, Lehongre, Morillon, Giraud, & Andreas, 2010). Results from the current investigation are evidence that sICA and dipole fitting can be used to estimate where particular EEG patterns are arising within the brain. As expected, IC clusters were identified for nodes in each of the three neural networks hypothesized to influence MW and focused attention (see Figures 5 through 9). Furthermore, few of the IC clusters found were in non-relevant brain areas, suggesting our sICA analysis was picking up the neural sources hypothesized to be essential for the study task. Though most of the neural network nodes found by Hasenkamp and colleagues (2011) were represented in the sICA results from the current study, several nodes were not represented. Independent component analysis clustering methods are limited in the number of nodes they can reliably identify (Cohen, 2014), so EEG source localization is restricted in how many nodes it can examine simultaneously.

As the present study aimed to examine a small number of neural network nodes within the FPCN, DAN, and DMN that were found by previous studies, the sICA results were adequate for the replication of node activations (see Table 1). Clustering results from the DMN identified by sICA were quite robust, with most participants contributing an IC to clusters from the bilateral PCC, bilateral PPC, and vmPFC (see Figure 7). The DAN had similarly strong representation in clusters from the bilateral primary sensory and motor cortices and a cluster in the mid-cingulate cortex (see Figure 8). Several nodes of the FPCN were reliably detected, including the dACC and bilateral IPC (see Figure 0). Nodes at the right dlPFC and insular cortices were also found, though these clusters had relatively few participants contributing ICs. Although EEG activations were evaluated for all possibly relevant clusters, the exploratory results beyond the stated hypotheses should be viewed as tentative at best, especially considering the larger-than-average spread of these clusters and their relative proximity to other pertinent brain areas (e.g., temporal lobe). Although the current results are far from perfect and pale in comparison to the spatial resolution generated with fMRI, moderate success in replicating previous findings from Hasenkamp and colleagues (2011) was achieved through identifying the most important neural network nodes involved in MW and focused attention with EEG sICA.

Neural Network Node Activations

In an attempt to replicate findings from previous studies of network activation changes surrounding awareness of MW during meditation, the present investigation examined the time course of ERSPs generated from clusters within the FPCN, DAN, and DMN identified with sICA. Average activity within each of the main EEG frequency bands (i.e., delta, theta, alpha, beta, and gamma) was compared between four time epochs surrounding participant's awareness of their own MW (see Figure 11). A pattern of results emerged from the present investigation which closely replicated findings from two previous EEG ERSP studies (Braboszcz, & Delorme, 2011; Fix & Faust, 2017). Additionally, significant EEG activation changes occurred in nearly all the brain regions and time periods of interest found to display fMRI BOLD activation changes by Hasenkamp and colleagues (2011), though this replication was not complete due to divergent trends across frequency bands. Although extensive group differences in EEG activations were expected, few differences were found between regular meditators and novice meditator participants.

The most consistent pattern observed within the results from the present investigation was a widespread alpha, beta, and gamma increase, along with a more localized delta and theta decrease, following after participants noticed their mind had wandered away from the task. This close replication of findings from similarly designed EEG studies (Braboszcz, & Delorme, 2011; Fix & Faust, 2017) suggests this pattern of activations was not an anomaly and may be a reliable biomarker of MW suppression. Furthermore, the similarity in findings across breath counting and meditation tasks (see Figures 1 and 2) suggests that similar cognitive resources are recruited to suppress MW regardless of what cognitive task the participant is engaged in, and that FA meditation may not be training unique cognitive control mechanisms. The observed pattern of activations was most pronounced in nodes from the FPCN and DMN during time epochs that have been found to display changes in BOLD activations during meditation (Hasenkamp et al., 2011). Combined with significant connectivity increases between several pairs of FPCN and DMN nodes during these time epochs, results from the current study provide further support for the hypothesis that the replicated pattern of EEG activity represents the FPCN and DMN interactions associated with MW suppression.

The current study successfully replicated findings from Hasenkamp et al. (2011) by observing significant EEG changes in each target time window that BOLD alterations were found in regular meditators (see Tables 2,3 and 4). The replication was mixed, though, as BOLD alterations were only linked to EEG activity *increases*, regardless of whether the BOLD signal had increased or decreased in the previous study. Though contradictory at first glance, the divergent directionality in results may be a product of the differences in imaging modality and analytic technique employed by the two studies. It has been recently noted that fMRI analyses based on general linear models, like those employed by Hasenkamp et al. (2011), have difficulty separating the excitatory and inhibitor activity that simultaneously arises from overlapping neural networks, and that EEG and sICA-based approaches hold significant advantages in this domain (Xu et al., 2013; Xu, Calhoun, & Potenza, 2015). As such, the conflicting results may have been detected because the present investigation used EEG data and sICA, techniques which are better equipped to separate the excitatory and inhibitory communications simultaneously received by a specific neural node (Aoki et al., 2015; Delorme et al., 2013; Hassan, Dufor, Merlet, Berrou, & Wendling, 2014; Knyazev et al., 2016). For example, the coupling of increased alpha, beta, and gamma EEG activity found in the present study within the DMN during time epochs when the participants were likely attempting to suppress their MW may not denote one signal (e.g., suppression), but instead may represent a competition between multiple signals associated with inhibition and excitation. The irregularity of coupling between alpha, beta, and gamma activity across networks warrants future investigation to disambiguate whether each frequency band serves an independent purpose or network.

The present findings support the premise that frequency-specific activity and connectivity within and between networks has functional relevance (Jann, Kottlow, Dierks, Boesch, & Koenig, 2010; Kang, Liu, Miskovic, Keil, & Ding, 2016; Neuner et al., 2014). As hypothesized, significant increases in beta activity during the Aware epoch were apparent in several nodes of the FPCN and DAN in both groups, along with similar increases in three nodes of the DMN which were not observed as BOLD activations changes by Hasenkamp and colleagues (2011). These widespread beta increases likely represent the coordination of activity across networks aimed at inhibiting MW and refocusing attention through the suppression of DMN activity. This interpretation is supported by recent studies which found EEG beta and fMRI BOLD activity to be linked to DMN deactivation (Laufs et al., 2003a; 2003b) and inhibition of memories (Waldhauser, Johansson, & Hanslmayr, 2012). The beta increases observed during the Aware epoch continued into the Shift epoch and were joined by more nodes of the FPCN and DMN, with several nodes also displaying significant increases in alpha and gamma activity, suggesting the inhibitory activity was spreading across the two networks. Though increases in EEG activity appeared everywhere BOLD activations were found by Hasenkamp and colleagues (2011), many of the effects were only marginally significant, and a number of effects were also found outside the targeted windows.

Analyses beyond those aimed at replication detected several effects which deviated from the stated hypotheses and from the effects found in previous investigations (Hasenkamp et al., 2011). The only two nodes to show perfect replication of BOLD activations were nodes of the DMN, the right PCC and left PPC, which had significant activation differences limited to the MW and Shift epoch comparison. The delay in activation differences in these two nodes implies they were the last nodes within the DMN to be deactivated. In direct contradiction to the findings from Hasenkamp and colleagues (2011), most of the other nodes in all three networks generated significant increases in beta, some also with alpha and gamma, activity which started during the Aware epoch and continued through the Shift and Focus epochs. One explanation for this divergent finding may be that suppressing MW and refocusing attention on a target requires a longer-lasting interaction between networks than has been previously found. Another possibility is that the EEG analyses conducted in the present study were distinguishing simultaneous excitatory and inhibitory activity that went undetected in the original fMRI study. It is also possible that the regular meditators in the current investigation did not have sufficient expertise or regularity in daily practice to achieve the heightened cognitive control efficiency that was detected in the meditators of the Hasenkamp et al. (2011) study.

Contemplative theories and a growing body of research supports the assertion that long term meditation practice affects neuroplastic changes in cognitive control mechanisms. Although activation differences were expected between groups, relatively few were observed. In one notable exception, regular meditators displayed a small alpha activity increase in, and connectivity decrease between, the dACC and left PCC, while novice meditator participants exhibited the exact opposite dynamic. Because high alpha activity is often associated with DMN inhibition and deactivation (Klimesch, 2012), coordinated increases in dACC and PCC alpha activity in regular meditators during the Aware epoch could be interpreted as evidence that the FPCN had already initiated the deactivation of the DMN at this early time point, while novice meditator participants were still struggling to commence the alpha increase associated with MW suppression. Furthermore, high alpha activity in the FPCN has been linked to higher working memory load (Jensen, Gelfand, Kounios, & Lisman, 2002), which further suggests regular meditators in the present investigation had a FPCN which responded more quickly and robustly to inhibit the DMN than was apparent in novice meditator participants. Indeed, regular meditators displaying high alpha within the FPCN is one of the few reliable results found across EEG studies of long term regular meditators (Lomas, Ivtzan, & Fu, 2015).

Further group differences were evident as novice meditator participants displayed significant decreases in delta and theta activity immediately following their awareness of MW. These delta and theta reductions were not as widespread as changes in the higher frequency bands, and were limited to nodes from the cognitive control networks. This effect was most pronounced in the dACC, where regular meditators generated more overall delta and theta during the MW and Aware epochs than did novice meditators, and their theta band activity remained high through the Shift and Focus epochs while novice meditator participant’s theta returned to baseline levels after the Shift epoch. These findings are congruent with studies that have found regular meditators have consistently shown higher theta band activity than non-meditators (Lomas, Ivtzan, & Fu, 2015), increased delta activity in regular meditators has been linked to greater inhibition of emotional reactivity (Tei et al., 2009), and high theta activity has been associated with re-orienting attention (Dietl, Dirlich, Vogl, Jechner, & Strian, 1999) and increased task demands (Klimesch, Doppelmayr, Schimke, & Ripper, 1997) in non-meditators during a variety of cognitive tasks. The higher FPCN delta and theta activity observed in the present investigation can be interpreted as supporting the premise that regular meditators possess an enhanced ability to stay focused through sustained FPCN activation.

Connectivity Findings

Recent advances in the modeling of anatomical and functional neural networks have facilitated an explosion of studies which aim to examine network connectivity dynamics. Mental activities that are regularly repeated strengthen the physical connections between relevant network nodes, ultimately resulting in changes to the functional connectivity between neural networks that support those mental activities. Focused attention meditation should promote robust neuroplastic changes in the neural circuits associated with cognitive control and MW because the central activity of the practice involves a repetitive cycle of noticing when the mind has wandered away from the target of attention, disengaging from this MW, and refocusing attention back on to the target stimuli. The current investigation hoped to replicate findings from an fMRI study which found enhanced connectivity within and between networks among meditators with more lifetime practice (Hasenkamp & Barsalou, 2012). Therefore, it was hypothesized that connectivity within and between the DMN, FPCN, and DAN would be greater for both groups after they became aware of their own MW and would be greater overall for regular meditators than for novice meditator participants.

Correlated activity among target neural network nodes was examined for evidence of changes in connectivity across time epochs and between groups. Though the original intent of the present study was to investigate connectivity between clusters identified with sICA, problems with the results did not allow this planned analysis to be conducted, and representative electrodes were substituted in all subsequent connectivity analyses. Similarly to the cluster activation results reported above, connectivity findings were dominated by alpha, beta, and gamma effects, with fewer significant connectivity alterations in the delta and gamma frequency bands (see Tables 5 through 10). Main effects of time were observed in nearly all of the targeted windows, with both groups producing changes in connectivity between and within pertinent neural networks. Contrary to our stated hypotheses and the results from the original fMRI study (Hasenkamo & Barsalou, 2012), a number of group effects were observed which, more often than not, showed regular meditators with lower overall connectivity. Results from the current study provide clear evidence that neural network connectivity is altered in response to participants becoming aware of their MW and then refocusing their attention.

Traditional EEG-based connectivity studies have primarily used EEG activity at the electrode as the level of analysis (Rubinov & Sporns, 2014; van Diessen et al., 2015), though recent developments have facilitated some early work on brain source-level connectivity (e.g., Lehmann, Faber, Tei, Pascual-Marqui, Milz, & Kochi, 2012; Knyazev, Savostyanov, Bocharov, Tamozhnikov, & Saprigyn, 2016; Saggar et al., 2015; Sockeel, Schwartz, Pelegrini-Issac, & Benali, 2016). To date, no consensus has emerged to indicate the optimal strategy for conducting source-level connectivity analyses, as there are advantages and disadvantages to each approach (Grech et al., 2008; Jatoi, Kamel, Malik, Faye, & Begum, 2014).

The current investigation used an sICA-based source localization method which successfully identified neural network nodes within the three target networks, though the sICA solution did not produce consistent enough ICs across participants to conduct the source-level connectivity analysis as originally planned (Onton et al., 2015). The main reason for this failure was that many participants often had one, but not both, ICs for any given node pair. These inconsistencies were equally distributed across participants and clusters so that nearly all node pairs had an insufficient numbers of participants contributing ICs to both nodes within a given pair. As such, correlations among neural network node pairs would have been extremely underpowered and unreliable. Instead of conducting such an analysis, the present study conducted a more traditional electrode-level connectivity analysis by correlating frequency-specific power changes between representative electrode pairs across time within each targeted time window and comparing across epoch and group (Ferdek, van Rijn, & Wyczesany, 2016).

Connectivity changes between MW and the other three time epochs were widespread, with both groups producing frequency-specific alterations in nearly all of the targeted time windows observed to have BOLD effects in the previously reported fMRI study (Hasenkamp & Barsalou, 2012). Hypothesized node pair connectivity changes were found most consistently within the beta frequency band, often co-occurring with alpha and/or gamma band alterations. Such strong beta band correlation increases are likely associated with the recruitment of cognitive control resources needed to suppress MW, though other explanations are possible. Chand and Dhamala (2016) found similar increases in beta activity and connectivity with the dACC to be associated with participants becoming aware of salient features of a task, which may explain why so many neural nodes increased their beta connectivity with the dACC immediately before and during button presses in the present investigation. Increased alpha and beta connectivity being associated with MW suppression is also supported by findings that associate these effects with the inhibition of memory retrieval (Waldhauser et al., 2012). In the current results, beta connectivity changes diminished quickly over time, particularly for within-network connectivity, with relatively few connectivity differences lasting until the Focus epoch. This dynamic suggests the superfluous mental activity involved in MW (e.g., memory retrieval) had been successfully suppressed and less beta-mediated inhibitory connectivity with the FPCN was required.

Along with inhibiting memory functions, MW suppression also involves attention and emotion regulation. In line with this explanation, one study that found beta connectivity to be positively correlated with effortful emotion regulation (Reiser, Schulter, Weiss, Fink, Rominger, & Papousek, 2012). Increased frontal beta activity has also been associated with increased effort towards attention regulation during meditation in both first-time and long-term meditators (Tanaka et al., 2014). Though increased connectivity was found to be associated with active suppression in the above two studies, a smaller connectivity increase was observed in those less prone to rumination (Reiser et al., 2012) and in long-term meditators (Tanaka et al., 2014).

Indeed, findings from the current investigation provide limited support for the growing hypothesis that meditation experience has a curvilinear relationship with a variety of outcome measures, including network activity and connectivity (Lehmann et al., 2012; Saggar et al., 2015; Saggar et al., 2012). As a participant begins meditation practice for the first time, maximum mental effort is required to reduce cognitive and affective reactivity to a sufficient level to maintain focused attention (Wallace, 2006). As the new meditator continues their daily practice, it becomes easier for them to notice when their mind has wandered, disengage from their MW, and keep their attention focused (MacLean et al., 2010). Theory suggests neuroplasticity will increase the connectivity within and between the FCPN, DAN, and DMN in parallel to the increased mental effort expended during early meditation practice (Malinowski, 2013). Eventually, connectivity requirements should decrease as maintaining focused attention becomes more routine and effortless.

Group connectivity differences from the present study are in line with the curvilinear theory of meditation effects. Within most of the targeted windows, regular meditators produced lower overall connectivity in at least one frequency band compared to novice meditator participants. Both within- and between-network connectivity in the DMN and FPCN was higher among novice meditator participants, suggesting more coordinated activity was required to suppress MW for those individuals. Researchers who have found similar results have postulated that the lower connectivity displayed by regular meditators represents an enhanced efficiency in cognitive control (Lehmann et al., 2012; Saggar et al., 2015; Saggar et al., 2012). This theory, along with the majority of group differences in the current investigation, are directly contradictory to our original hypotheses and to evidence from the fMRI study which found a positive correlation between lifetime hours of meditation and the connectivity associated with MW suppression (Hasenkamp & Barsalou, 2012). One explanation for this divergence is that the BOLD connectivity increase represents a crude measure of more network activity, while the EEG results from the current study represent a more nuanced frequency-specific view of simultaneous excitatory and inhibitory communications.

Exploratory analyses revealed complex connectivity alterations across time, and differences between groups, outside of the time windows targeted for replication. Beta connectivity increased for both groups between the MW and Aware epochs for every node pair analyzed, along with many alpha and gamma band enhancements. In a similar fashion to the targeted comparisons, exploratory results showed regular meditators consistently produced lower connectivity between and within networks. Moreover, several group effects spanned all three epoch comparisons, lending further support to the notion that regular meditators require less connectivity to inhibit DMN activity, just as they expend less mental effort to suppress their MW (Garrison et al., 2013a; 2013b). Another possibility is that the lower overall connectivity among experienced meditators represents less self-referential processing, a central outcome purported to result from regular meditation practice (Wallace, 2006). Experimental findings show self-related MW to increase EEG connectivity (Andersen, 2009; Knyazev et al., 2016), meditators have been found to produce less self-related DMN activity and connectivity during meditation (Lehmann, Faber, Tei, Pascual-Marqui, Milz, & Kochi, 2012; Saggar et al., 2015). By repeatedly disengaging from self-related mental activity and working to maintain a non-judgmental and non-reactive cognitive and affective disposition, regular meditators may be reducing the stability and influence of the self through altered connectivity patterns.

Limitations and Future Directions

The aim of the present study was to replicate findings from similarly designed studies that used fMRI and EEG data. Although our findings closely replicated previous studies, a large portion of the results from the current investigation are exploratory. Time-frequency analyses of EEG data, like the ERSPs used here, are still relatively rare within psychological studies, and are even less common among studies of MW. Therefore, the current study had little foundation to make frequency-band-specific hypotheses about the time windows and network nodes of interest. Despite the preliminary nature of the current investigation, it was promising that we replicated a pattern of results found in previous studies, and this fact will strengthen the ability of future studies to make more hypothesis-driven frequency-specific predictions.

Additionally, because ERSP analyses involve highly complex and multidimensional data, the number of statistical tests conducted by the present investigation was many times more than in a traditional fMRI analysis. Bonferroni corrections were applied to replications of time window- and network node-specific activations and connectivity to control for Type 1 error, consistent with other studies utilizing time-frequency EEG data (Cohen, 2014), though these corrections were relatively liberal. The current study had a large number of findings with p-values near the statistically significant threshold, which may be a counterweight against the possibility that these effects are mostly false positives. Indeed, the sheer number of marginally significant findings is promising, and studies with larger sample sizes should attempt to replicate results from the current investigation. With that being said, conclusions drawn from marginally significant results and those from the reported uncorrected exploratory results should be considered tentative at best. The main purpose of presenting exploratory results from the current investigation was to support future studies that use time-frequency EEG data.

Attempting to replicate fMRI findings with EEG data, as the current study did, had both positive and negative consequences. The spatial resolution of fMRI results, and the activation plots they produce, are very compelling to researchers attempting to uncover the neural mechanisms associated with specific psychological processes. Unfortunately, the spatial resolution afforded to fMRI analyses comes at the expense of temporal resolution. This tradeoff is problematic when examining psychological and neural processes which occur and change rapidly. Despite the advantage that EEG methods have over fMRI in the temporal domain, the current study maintained the targeted time windows used in the previous fMRI studies. This decision was made to facilitate a clean replication of source-localized activations at the expense of a more temporally-sensitive examination of network dynamics.

Source localization of EEG data is still a relatively new and controversial family of techniques that has only recently been gaining empirical support. The Inverse Problem states that definitive source localization is not possible because of the vast number of alternate possible solutions for any given scalp-recorded data pattern. Without knowing exactly how an individual’s cortex is folded into gyri and sulci, the exact shape of the electrical field generated by the neural node, and how that electrical field is being altered from volume conduction as it passes through other brain areas and the scalp, EEG source localization results are estimates at best. As such, sICA results from the current study should be considered estimates. With that being said, source localization methods have been gaining wider support in recent years. A variety of source localization techniques have been developed and compared (Delorme et al., 2012; Grech et al., 2008; Jatoi et al., 2014), and simultaneous EEG and fMRI studies have examined the convergent validity between these two imaging modalities (Jann et al., 2010; Sockeel et al., 2016). The overall finding from studies examining the validity of EEG source localization methods is that, though there is no one-size-fits-all solution and future work is clearly needed, the current techniques provide adequately robust estimates.

The fact that button presses used in the current study were not locked to any concrete stimulus also contributed to the decision to examine EEG data averaged over relatively large time windows (i.e., 3 seconds). The vast majority of EEG studies investigate so-called evoked EEG dynamics, which refer to neural responses that are time-locked to a stimulus and therefore thought to be associated only with processing that specific stimulus. Without a solid stimulus-locked event, the current results likely represent both evoked and so-called induced EEG dynamics, meaning activity associated with background neural processing that is not time-locked to a specific stimulus.

As an illustration of how the weak events (i.e., button presses) used in the present study may have contributed to noisy EEG results, consider the following observation. Although all participants were given the same instructions about when to press the button "once you notice your mind has wandered, press the button and return your attention to the sensations of the breath", it is likely that there was significant variability in the timing of each individual's psychological and behavioral processes involved in the button presses. For example, some participants may have noticed their MW, taken a few seconds to collect their thoughts and refocus attention, and *then* pressed the button to indicate they were refocused on the sensations of their breath. Conversely, other participants may have immediately pressed the button upon noticing their MW, *then* collected their thoughts and refocused their attention. Without more detailed introspective data, it is difficult to be confident that all participants were timing their button presses in a sufficiently similar fashion. Significant timing variability between participants could mask otherwise easily detectable patterns within the EEG data.

It should also be noted that the button presses used to indicate awareness of MW during meditation likely had unintended effects on the psychological and neural processes of the participants. Anecdotally, more than one regular meditator expressed surprise at how much pressing the button changed their normal meditative experience. It was reported that pressing the button during meditation introduced more self-evaluative thoughts than were typical. As such, it is possible that much of the observed EEG dynamics were actually associated with participants monitoring their performance and berating themselves for their lack of focus instead of primarily being associated with MW suppression and refocusing attention. Future studies using a similar design to the present investigation would benefit from collecting qualitative reports and using them to give participants feedback about how they should be timing their button presses.

Another shortcoming of the current study was the variability in meditative traditions practiced by participants. Though some studies have found few differences between meditative traditions (Lehman et al., 2012), it is likely that psychological and neural mechanisms are differentially altered depending on the specific practices within a given meditative tradition (Slagter et al., 2011). Indeed, the field is in desperate need of studies that more carefully examine the effects of different meditation practices. Though it was not possible to control for differences between meditative traditions in the current study, all participants did practice the same type of meditation three times prior to, and during, the EEG testing. While this design aspect meant that novice meditator participants were not complete novices, it ensured that all participants were familiar with the practice so that we could be confident that we were examining the neural dynamics specifically associated with FAM.

The current investigation suffered from several other design problems. While we recruited an average number of participants (*N* = 46) for an EEG study, a larger sample size would have increased the power to detect smaller effects and would have likely pushed a number of the marginally significant effects over the statistical threshold. Additionally, a lack of pre-post design limits the causal inferences that can be made from the current results, as those who self-selected into their meditative practice may share other characteristics not measured by the present study. Experimenters that trained participants and collected EEG data were not blind to group assignment, which may have subtly influenced the way participants were treated. Importantly, participants had relatively low numbers of trials during the meditation, leading to results which are not immune to the effects of artifacts and other uncommon EEG features. Despite the low trial count, our results closely replicated ERSP findings from a previous study utilizing a breath counting task and many more trials, suggesting our main findings represent a reliable feature of neural dynamics.

Conclusions

Replicating findings from similarly designed studies, the current investigation found a robust pattern of EEG activity surrounding participant’s awareness of their MW during FAM. Similar to results from one EEG study (Braboszcz & Delorme, 2011), a trend emerged such that participant’s alpha, beta, and gamma band activity often increased while delta and theta band activity tended to decrease immediately following awareness of MW. These alterations diminished over time and neural activity returned to baseline within a few seconds, presumably because participants had successfully suppressed their MW and reoriented attention to their intended focus. The activation changes found in the present study likely represent the DMN, FPCN, and DAN interacting to suppress MW and refocus attention. Contrary to expectations, few group differences in EEG activity were observed between regular meditators and novice meditator participants.

Consistent with a previous study on MW during FAM (Hasenkamp & Barsalou, 2012), both regular meditators and novice meditator participants displayed increased neural network connectivity soon after they noticed their mind had wandered. Surprisingly, regular meditators often generated lower overall connectivity and smaller increases between and within networks, indicating they may possess enhanced network efficiency. This interpretation is consistent with the hypothesis that the regular practice of FAM, which is dominated by repeatedly noticing MW and refocusing attention, makes it easier to suppress MW and maintain focused attention.

The current study provides preliminary support for the use of sICA to localize the sources of patterns of EEG data recorded at the scalp. Significant ERSPs were observed in nearly every targeted window for each network node that displayed BOLD alterations in two previous fMRI studies (Hasenkamp et al., 2011; Hasenkamp & Barsalou, 2012). However, this replication opens up new questions, as novel frequency-specific effects were observed which directly contradicted those found with fMRI. By examining network interactions across EEG frequency bands, future studies will be better equipped to examine neural network communication in a more dynamic and complete manner.

REFERENCES

Andersen, S. B., Moore, R. A., Venables, L., & Corr, P. J. (2009). Electrophysiological correlates of anxious rumination. *International Journal Of Psychophysiology, 71(2)*, 156-169. doi:10.1016/j.ijpsycho.2008.09.004

Anticevic, A., Cole, M. W., Murray, J. D., Corlett, P. R., Wang, X. J., & Krystal, J. H. (2012). The role of default network deactivation in cognition and disease. *Trends in Cognitive Sciences*, *16*(12), 584-592.

Aoki, Y., Ishii, R., Pascual-Marqui, R. D., Canuet, L., Ikeda, S., Hata, M., ... & Iwase, M. (2015). Detection of EEG-resting state independent networks by eLORETA-ICA method. *Frontiers in human neuroscience*, 9.

Baer, R. A., Smith, G. T., Lykins, E., Button, D., Krietemeyer, J., Sauer, S., ... & Williams, J. M. G. (2008). Construct validity of the five facet mindfulness questionnaire in meditating and nonmeditating samples. *Assessment*, *15*(3), 329-342.

Baird, B., Smallwood, J., Mrazek, M. D., Kam, J. W., Franklin, M. S., & Schooler, J. W. (2012). Inspired by distraction mind wandering facilitates creative incubation. *Psychological Science*, 0956797612446024.

Baird, B., Smallwood, J., & Schooler, J. W. (2011). Back to the future: autobiographical planning and the functionality of mind-wandering. *Consciousness and cognition, 20*(4), 1604-1611.

Başar, E., Başar-Eroglu, C., Karakaş, S., & Schürmann, M. (2001). Gamma, alpha, delta, and theta oscillations govern cognitive processes. *International Journal of Psychophysiology*, *39*(2), 241-248.

Braboszcz, C., & Delorme, A. (2011). Lost in thoughts: neural markers of low alertness during mind wandering. *Neuroimage*, *54*(4), 3040-3047.

Brewer, J. A., Garrison, K. A., & Whitfield-Gabrieli, S. (2013). What about the “self” is processed in the posterior cingulate cortex? *Frontiers in human neuroscience,* 7.

Brewer, J. A., Worhunsky, P. D., Gray, J. R., Tang, Y. Y., Weber, J., & Kober, H. (2011). Meditation experience is associated with differences in default mode network activity and connectivity. *Proceedings of the National Academy of Sciences*, *108*(50), 20254-20259.

Buckner, R. L., Andrews-Hanna, J. R., & Schacter, D. L. (2008). The brain's default network. *Annals of the New York Academy of Sciences*, *1124*(1), 1-38.

Cahn, B. R., Delorme, A., & Polich, J. (2013). Event-related delta, theta, alpha and gamma correlates to auditory oddball processing during Vipassana meditation. *Social Cognitive and Affective Neuroscience*, *8*(1), 100-111.

Felicity Callard, Daniel S Margulies. (2011) The Subject at Rest: Novel conceptualizations of self and brain from cognitive neuroscience's study of the ‘resting state’. *Subjectivity 4,* 3227-257.

\Chand, G. B., & Dhamala, M. (2016). The salience network dynamics in perceptual decision-making. *Neuroimage,* 13485-93. doi:10.1016/j.neuroimage.2016.04.018

Chang, Y. C., & Huang, S. L. (2012). The influence of attention levels on psychophysiological responses. *International Journal of Psychophysiology, 86(1),* 39-47.

Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences, 106*(21), 8719-8724.

Christoff, K., Gordon, A., Smith, R., & Vancouver, B. C. (2011). The role of spontaneous thought in human cognition. *Neuroscience of decision making*, 259-284.

Christopher, M. S., Christopher, V., & Charoensuk, S. (2009). Assessing 'Western' mindfulness among Thai Theravāda Buddhist Monks. *Mental Health, Religion & Culture, 12*(3), 303-314. doi:10.1080/13674670802651487

Christopher, M. S., Neuser, N. J., Michael, P. G., & Baitmangalkar, A. (2012). Exploring the psychometric properties of the five facet mindfulness questionnaire. *Mindfulness*, *3*(2), 124-131.

Cheyne, J., Solman, G. J., Carriere, J. S., & Smilek, D. (2009). Anatomy of an error: A bidirectional state model of task engagement/disengagement and attention-related errors. *Cognition*, *111*(1), 98-113.

Cohen, M. X. (2014). *Analyzing neural time series data: theory and practice.* MIT Press. Chicago

Cohen, J., & Cohen, P. (1983). *Applied multiple regression/correlation analysis for the behavioral sciences.* Hillsdale, NJ: Erlbaum.

Delorme, A., Sejnowski, T., & Makeig, S. (2007). Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. *Neuroimage, 34*(4), 1443-1449.

Delorme, A., Kothe, C., Vankov, A., Bigdely-Shamlo, N., Oostenveld, R., Zander, T. O., & Makeig, S. (2010). MATLAB-based tools for BCI research. In *Brain-Computer Interfaces* (pp. 241-259). Springer London.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9-21.

Delorme, A., Palmer, J., Onton, J., Oostenveld, R., & Makeig, S. (2012). Independent EEG sources are dipolar. *PloS one*, *7(2),* e30135.

Dietl, T., Dirlich, G., Vogl, L., Lechner, C., & Strian, F., (1999). Orienting response and frontal midline theta activity: a somatosensory spectral perturbation study. *Clinical Neurophysiology, 110 (7)*, 1204–1209, http://dx.doi.org/10.1016/S1388-2457(99)00057-7.

Farb, N. A., Segal, Z. V., Mayberg, H., Bean, J., McKeon, D., Fatima, Z., & Anderson, A. K. (2007). Attending to the present: mindfulness meditation reveals distinct neural modes of self-reference. *Social Cognitive and Affective Neuroscience*, *2*(4), 313-322.

Fellrath, J., Mottaz, A., Schnider, A., Guggisberg, A. G., & Ptak, R. (2016). Theta-band functional connectivity in the dorsal fronto-parietal network predicts goal-directed attention. *Neuropsychologia*, 9220-30. doi:10.1016/j.neuropsychologia.2016.07.012

Ferdek, M. A., Rijn, C. M., & Wyczesany, M. (2016). Depressive rumination and the emotional control circuit: An eeg localization and effective connectivity study. *Cognitive, Affective & Behavioral Neuroscience.* doi:10.3758/s13415-016-0456-x

Fingelkurts, A. A., & Fingelkurts, A. A. (2011). Persistent operational synchrony within brain default-mode network and self-processing operations in healthy subjects. *Brain and cognition, 75*(2), 79-90.

Fix, S.T., & Faust, M.E. (2017). *Bringing the Mind Back: Brain Oscillations Associated with Refocusing Attention after a Mind Wandering Episode.* Unpublished Manuscript.

Froeliger, B., Garland, E. L., Kozink, R. V., Modlin, L. A., Chen, N. K., McClernon, F. J., ... & Sobin, P. (2012). Meditation-state functional connectivity (msFC): strengthening of the dorsal attention network and beyond. *Evidence-Based Complementary and Alternative Medicine*, 2012.

Gao, W., & Lin, W. (2012). Frontal parietal control network regulates the anti-correlated default and dorsal attention networks. *Human brain mapping, 33(1),* 192-202.

Garrison, K. A., Santoyo, J. F., Davis, J. H., Thornhill IV, T. A., Kerr, C. E., & Brewer, J. A. (2013a). Effortless awareness: using real time neurofeedback to investigate correlates of posterior cingulate cortex activity in meditators' self-report. *Frontiers in Human Neuroscience, 7*.

Garrison, K. A., Scheinost, D., Worhunsky, P. D., Elwafi, H. M., Thornhill IV, T. A., Thompson, E., ... & Brewer, J. A. (2013b). Real-time fMRI links subjective experience with brain activity during focused attention. *NeuroImage, 81*, 110-118.

Gerlach, K. D., Spreng, R. N., Gilmore, A. W., & Schacter, D. L. (2011). Solving future problems: default network and executive activity associated with goal-directed mental simulations. *Neuroimage, 55*(4), 1816-1824.

Goldin, P., Ramel, W., & Gross, J. (2009). Mindfulness meditation training and self-referential processing in social anxiety disorder: Behavioral and neural effects. *Journal of Cognitive Psychotherapy*, *23*(3), 242-257.

Grech, R., Cassar, T., Muscat, J., Camilleri, K. P., Fabri, S. G., Zervakis, M., ... & Vanrumste, B. (2008). Review on solving the inverse problem in EEG source analysis. *Journal of Neuroengineering and Rehabilitation*, *5*(1), 1.

Hassan, M., Dufor, O., Merlet, I., Berrou, C., & Wendling, F. (2014). EEG source connectivity analysis: from dense array recordings to brain networks. *PloS one*, *9*(8), e105041.

Hasenkamp, W., Wilson-Mendenhall, C. D., Duncan, E., & Barsalou, L. W. (2012). Mind wandering and attention during focused meditation: a fine-grained temporal analysis of fluctuating cognitive states. *Neuroimage*, *59*(1), 750-760.

Hasenkamp, W., & Barsalou, L. W. (2012). Effects of meditation experience on functional connectivity of distributed brain networks. *Frontiers in human neuroscience*, *6*, 38.

Hussain, D., & Bhushan, B. (2010). Psychology of meditation and health: Present status and future directions. *International Journal of Psychology and Psychological Therapy*, *10*(3), 439-451.

Ishii, R., Canuet, L., Herdman, A., Gunji, A., Iwase, M., Takahashi, H., ... & Takeda, M. (2009). Cortical oscillatory power changes during auditory oddball task revealed by spatially filtered magnetoencephalography. *Clinical Neurophysiology, 120(3),* 497-504.

Jatoi, M. A., Kamel, N., Malik, A. S., Faye, I., & Begum, T. (2014). A survey of methods used for source localization using EEG signals. *Biomedical Signal Processing and Control*, *11*, 42-52.

Jensen, O., Gelfand, J., Kounios, J., & Lisman, J. E. (2002). Oscillations in the alpha band (9–12 Hz) increase with memory load during retention in a short-term memory task. *Cerebral Cortex*, *12*(8), 877-882.

Josipovic, Z., Dinstein, I., Weber, J., & Heeger, D. J. (2012). Influence of meditation on anti-correlated networks in the brain. *Frontiers in Human Neuroscience*, *5*, 183-194.

Jung, K.-Y., Seo, D.-W., Na, D. L., Chung, C.-S., Lee, I. K., Oh, K., … Jung, H.-K. (2007). Source localization of periodic sharp wave complexes using independent component analysis in sporadic Creutzfeldt-Jakob disease. *Brain Research, 1143*, 228–37.

doi:10.1016/j.brainres.2007.01.127

Kam, J. Y., Brenner, C. A., Handy, T. C., Boyd, L. A., Liu-Ambrose, T., Lim, H. J., & ... Campbell, K. L. (2016). Sustained attention abnormalities in breast cancer survivors with cognitive deficits post chemotherapy: An electrophysiological study. *Clinical Neurophysiology, 127*(1), 369-378. doi:10.1016/j.clinph.2015.03.007

Kamarajan, C., Porjesz, B., Jones, K. A., Choi, K., Chorlian, D. B., Padmanabhapillai, A., ... & Begleiter, H. (2004). The role of brain oscillations as functional correlates of cognitive systems: a study of frontal inhibitory control in alcoholism. *International Journal of Psychophysiology*, *51*(2), 155-180.

Kahana, M. J. (2006). The cognitive correlates of human brain oscillations. *The Journal of Neuroscience, 26(6)*, 1669-1672.

Keune, P. M., Bostanov, V., Hautzinger, M., & Kotchoubey, B. (2013). Approaching dysphoric mood: State-effects of mindfulness meditation on frontal brain asymmetry. *Biological Psychology, 93*(1), 105-113. doi:10.1016/j.biopsycho.2013.01.016

Klimesch, W., Doppelmayr, M., Schimke, H., & Ripper, B., (1997). Theta synchronizationand alpha desynchronization in a memory task. *Psychophysiology 34* (2),169–176, http://dx.doi.org/10.1111/j.1469-8986.1997.tb02128.x.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in cognitive sciences*, *16*(12), 606-617.

Knyazev, G. G. (2013). EEG correlates of self-referential processing. Frontiers In Human *Neuroscience*, *7*. doi:10.3389/fnhum.2013.00264

Knyazev, G. G., Slobodskoj-Plusnin, J. Y., Bocharov, A. V., & Pylkova, L. V. (2011). The default mode network and EEG alpha oscillations: An independent component analysis. *Brain Research*, *1402*, 67-79.

Knyazev, G. G., Savostyanov, A. N., Bocharov, A. V., Tamozhnikov, S. S., & Saprigyn, A. E. (2016). Task-positive and task-negative networks and their relation to depression: EEG beamformer analysis. *Behavioural brain research, 306*, 160-169.

Kok, B. E., Waugh, C. E., & Fredrickson, B. L. (2013). Meditation and health: The search for mechanisms of action. *Social and Personality Psychology Compass, 7*(1), 27-39.

Laufs, H., Krakow, K., Sterzer, P., Eger, E., Beyerle, A., Salek-Haddadi, A., & Kleinschmidt, A. (2003a). Electroencephalographic signatures of attentional and cognitive default modes in spontaneous brain activity fluctuations at rest. *Proceedings of the National Academy of Sciences*, *100*(19), 11053-11058.

Laufs, H., Kleinschmidt, A., Beyerle, A., Eger, E., Salek-Haddadi, A., Preibisch, C., & Krakow, K. (2003b). EEG-correlated fMRI of human alpha activity. *Neuroimage*, *19*(4), 1463-1476.

Lee, E. H. (2012). Review of the psychometric evidence of the perceived stress scale. Asian Nursing Research, 6(4), 121-127.

Lehmann, D., Faber, P. L., Tei, S., Pascual-Marqui, R. D., Milz, P., & Kochi, K. (2012). Reduced functional connectivity between cortical sources in five meditation traditions detected with lagged coherence using EEG tomography. *Neuroimage, 60*(2), 1574-1586.

Lenartowicz, A., Delorme, A., Walshaw, P. D., Cho, A. L., Bilder, R. M., McGough, J. J., ... & Loo, S. K. (2014). Electroencephalography correlates of spatial working memory deficits in attention-deficit/hyperactivity disorder: vigilance, encoding, and maintenance. *The Journal of Neuroscience*, *34*(4), 1171-1182.

Lomas, T., Ivtzan, I., & Fu, C. Y. (2015). A systematic review of the neurophysiology of mindfulness on EEG oscillations. *Neuroscience And Biobehavioral Reviews, 57*, 401-410. doi:10.1016/j.neubiorev.2015.09.018

Lutz, A., Slagter, H. A., Rawlings, N. B., Francis, A. D., Greischar, L. L., & Davidson, R. J. (2009). Mental training enhances attentional stability: Neural and behavioral evidence. *The Journal of Neuroscience*, *29*(42), 13418-13427.

Lutz, A., Slagter, H. A., Dunne, J. D., & Davidson, R. J. (2008). Attention regulation and monitoring in meditation. *Trends in Cognitive Sciences*, *12*(4), 163-169.

MacLean, K. A., Ferrer, E., Aichele, S. R., Bridwell, D. A., Zanesco, A. P., Jacobs, T. L., & ... Saron, C. D. (2010). Intensive meditation training improves perceptual discrimination and sustained attention. *Psychological Science, 21*(6), 829-839. doi:10.1177/0956797610371339

Malinowski, P. (2013). Neural mechanisms of attentional control in mindfulness meditation. *Frontiers in Neuroscience*, *7*.

Marchetti, I., Koster, E. H., & De Raedt, R. (2012). Mindwandering heightens the accessibility of negative relative to positive thought. *Consciousness and Cognition*, *21*(3), 1517-1525.

MathWorks, Inc. (2005). *MATLAB: The language of technical computing. Desktop tools and development environment, version 7* (Vol. 9). MathWorks.

McVay, J. C., & Kane, M. J. (2010). Does Mind Wandering Reflect Executive Function or Executive Failure? Comment on Smallwood and Schooler (2006) and Watkins (2008). *Psychological Bulletin, 136*(2), 188-197. doi:10.1037/a0018298

McVay, J. C., & Kane, M. J. (2012). Drifting from slow to “d'oh!”: Working memory capacity and mind wandering predict extreme reaction times and executive control errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(3), 525.

Meltzer, J. A., Negishi, M., Mayes, L. C., & Constable, R. T. (2007). Individual differences in EEG theta and alpha dynamics during working memory correlate with fMRI responses across subjects. *Clinical Neurophysiology*, *118*(11), 2419-2436.

Mennes, M., Wouters, H., Vanrumste, B., Lagae, L., & Stiers, P. (2010). Validation of ICA as a tool to remove eye movement artifacts from EEG/ERP. *Psychophysiology, 47*(6), 1142-1150.

Mooneyham, B. W., & Schooler, J. W. (2013). The Costs and Benefits of Mind-Wandering: A Review. *Canadian Journal Of Experimental Psychology*, *67*(1), 11-18. doi:10.1037/a0031569

Onton, J., Westerfield, M., Townsend, J., & Makeig, S. (2006). Imaging human EEG dynamics using independent component analysis. *Neuroscience & Biobehavioral Reviews*, *30*(6), 808-822.

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

Piai, V., Roelofs, A., Rommers, J., Dahlslätt, K., & Maris, E. (2015). Withholding planned speech is reflected in synchronized beta-band oscillations. *Frontiers In Human Neuroscience*, *9.*

Poerio, G. L., Totterdell, P., & Miles, E. (2013). Mind-wandering and negative mood: Does one thing really lead to another? *Consciousness and Cognition*, *22*(4), 1412-1421.

Putnam, K. M., & McSweeney, L. B. (2008). Depressive symptoms and baseline prefrontal EEG alpha activity: A study utilizing Ecological Momentary

Assessment. *Biological Psychology, 77*(2), 237-240. doi:10.1016/j.biopsycho.2007.10.010

Qin, P., & Northoff, G. (2011). How is our self-related to midline regions and the default-mode network? *Neuroimage, 57(3),* 1221-1233.

Qu, W., Ge, Y., Xiong, Y., Carciofo, R., Zhao, W., & Zhang, K. (2015). The relationship between mind wandering and dangerous driving behavior among Chinese drivers. *Safety Science, 78*, 41-48. doi:10.1016/j.ssci.2015.04.016

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences*, *98*(2), 676-682.

Randall, J. G., Oswald, F. L., & Beier, M. E. (2014). Mind-wandering, cognition, and performance: A theory-driven meta-analysis of attention regulation. *Psychological bulletin, 140*(6), 1411.

Rubinov, M., & Sporns, O. (2010). Complex network measures of brain connectivity: uses and interpretations. *Neuroimage, 52*(3), 1059-1069.

Sadaghiani, S., Scheeringa, R., Lehongre, K., Morillon, B., Giraud, A. L., D'Esposito, M., & Kleinschmidt, A. (2012). Alpha-band phase synchrony is related to activity in the fronto-parietal adaptive control network. *The Journal of Neuroscience, 32*(41), 14305-14310.

Sahdra, B. K., MacLean, K. A., Ferrer, E., Shaver, P. R., Rosenberg, E. L., Jacobs, T. L., ... &Saron, C. D. (2011). Enhanced response inhibition during intensive meditation training predicts improvements in self-reported adaptive socioemotional functioning. *Emotion-APA, 11*(2), 299.

Scheeringa, M. S., & Zeanah, C. H. (2008). Reconsideration of harm's way: Onsets and comorbidity patterns of disorders in preschool children and their caregivers following Hurricane Katrina. *Journal of Clinical Child & Adolescent Psychology*, *37*(3), 508-518.

Schoenberg, P. A., & Speckens, A. M. (2014). Modulation of induced frontocentral theta (Fm-θ) event-related (de-)synchronisation dynamics following mindfulness-based cognitive therapy in major depressive disorder. *Cognitive Neurodynamics, 8*(5), 373-388. doi:10.1007/s11571-014-9294-0

Siebenhühner, F., Lobier, M., Wang, S. H., Palva, S., & Palva, J. M. (2016). *Measuring large-scale synchronization with human MEG and EEG: challenges and solutions.* In Multimodal Oscillation-based Connectivity Theory (pp. 1-18). Springer International Publishing.

Slagter, H. A., Davidson, R. J., & Lutz, A. (2011). Mental training as a tool in the neuroscientific study of brain and cognitive plasticity. *Frontiers in Numan Neuroscience*, *5,* 17-29.

Smallwood, J., Brown, K., Baird, B., & Schooler, J. W. (2012). Cooperation between the default mode network and the frontal–parietal network in the production of an internal train of thought. *Brain Research*, *1428,* 60-70.

Smallwood, J., Fitzgerald, A., Miles, L. K., & Phillips, L. H. (2009). Shifting moods, wandering minds: negative moods lead the mind to wander. Emotion, 9(2), 271.

Smallwood, J., & O'Connor, R. C. (2011). Imprisoned by the past: unhappy moods lead to a retrospective bias to mind wandering. *Cognition & Emotion, 25*(8), 1481-1490.

Smallwood, J., O'Connor, R. C., Sudbery, M. V., & Obonsawin, M. (2007). Mind-wandering and dysphoria. *Cognition and Emotion, 21*(4), 816-842.

Sockeel, S., Schwartz, D., Pélégrini-Issac, M., & Benali, H. (2016). Large-Scale Functional Networks Identified from Resting-State EEG Using Spatial ICA. *PloS one*, *11*(1), e0146845.

Sood, A., & Jones, D. T. (2013). On mind wandering, attention, brain networks, and meditation. *Explore: The Journal of Science and Healing*, *9*(3), 136-141.

Spreng, R. N., & Grady, C. L. (2010). Patterns of brain activity supporting autobiographical memory, prospection, and theory of mind, and their relationship to the default mode network. *Journal of cognitive neuroscience, 22*(6), 1112-1123.

Spreng, R. N., Sepulcre, J., Turner, G. R., Stevens, W. D., & Schacter, D. L. (2013). Intrinsic architecture underlying the relations among the default, dorsal attention, and frontoparietal control networks of the human brain. *Journal of Cognitive Neuroscience*, *25*(1), 74-86.

Storm, B. C., & Bui, D. C. (2016). Individual differences in mind wandering while reading predict lower rates of analogical transfer. *Learning & Individual Differences*, *51*, 427-432. doi:10.1016/j.lindif.2015.02.001

Tei, S., Faber, P. L., Lehmann, D., Tsujiuchi, T., Kumano, H., Pascual-Marqui, R. D., & ... Kochi, K. (2009). Meditators and non-meditators: EEG source imaging during resting. *Brain Topography, 22*(3), 158-165. doi:10.1007/s10548-009-0107-4

Van Diessen, E., Numan, T., Van Dellen, E., Van Der Kooi, A. W., Boersma, M., Hofman, D., ... & Stam, C. J. (2015). Opportunities and methodological challenges in EEG and MEG resting state functional brain network research. *Clinical Neurophysiology*, *126*(8), 1468-1481.

Vago, D. R., & Zeidan, F. (2016). The brain on silent: mind wandering, mindful awareness, and states of mental tranquility. *Annals Of The New York Academy Of Sciences*, *1373*(1), 96-113.

Vincent, J. L., Kahn, I., Snyder, A. Z., Raichle, M. E., & Buckner, R. L. (2008). Evidence for a frontoparietal control system revealed by intrinsic functional connectivity. *Journal of Neurophysiolology*, *100*(6), 3328-3342.

Waldhauser, G. T., Johansson, M., & Hanslmayr, S. (2012). Alpha/beta oscillations indicate inhibition of interfering visual memories. *The Journal of neuroscience*, *32*(6), 1953-1961.

Wallace, B. A. (2006). *The attention revolution: Unlocking the power of the focused mind.* Simon and Schuster.

Whitfield-Gabrieli, S., Moran, J. M., Nieto-Castañón, A., Triantafyllou, C., Saxe, R., & Gabrieli, J. D. (2011). Associations and dissociations between default and self-reference networks in the human brain. *Neuroimage*, *55*(1), 225-232.

Wyczesany, M., Grzybowski, S. J., & Kaiser, J. (2015). Emotional reactivity to visual content as revealed by ERP component clustering. *Journal of Psychophysiology*, *29*(4), 135–146. doi:10.1027/0269-8803/a000145

Xu, J., Calhoun, V. D., & Potenza, M. N. (2015). The absence of task-related increases in BOLD signal does not equate to absence of task-related brain activation. *Journal of neuroscience methods*, *240*, 125-127.

Xu, J., Zhang, S., Calhoun, V. D., Monterosso, J., Li, C. S. R., Worhunsky, P. D., ... & Potenza, M. N. (2013). Task-related concurrent but opposite modulations of overlapping functional networks as revealed by spatial ICA. *Neuroimage, 79*, 62-71.

Zanesco, A. P., King, B. G., MacLean, K. A., Jacobs, T. L., Aichele, S. R., Wallace, B. A., & ... Saron, C. D. (2016). Meditation training influences mind wandering and mindless reading. *Psychology Of Consciousness: Theory, Research, And Practice, 3*(1), 12-33. doi:10.1037/cns0000082

Zordan, L., Sarlo, M., & Stablum, F. (2008). ERP components activated by the “GO!” and “WITHHOLD!” conflict in the random Sustained Attention to Response Task. *Brain and Cognition*, *66*(1), 57-64.

Zeidan, F., Johnson, S. K., Diamond, B. J., David, Z., & Goolkasian, P. (2010). Mindfulness meditation improves cognition: Evidence of brief mental training. *Consciousness and Cognition, 19(2)*, 597-605.

Table 1.

Location and Density Information for each Dipole Cluster identified with sICA.

		Centroid MNI Coordinates			Cluster Standard Deviation			Cluster Standard Error		
	# of Participants per cluster	X	Y	Z	X	Y	Z	X	Y	Z
FPCN										
dACC	27	29	-4	39	11	10	9	2	2	1
right dlPFC	13	38	-42	15	13	13	12	3	3	3
right IPC	25	-23	-45	16	12	12	14	2	2	2
left IPC	22	-24	35	37	10	10	10	2	2	2
DAN										
right M1	21	9	-35	46	11	10	10	2	2	2
left M1	25	14	36	38	11	11	10	2	2	2
pACC	18	-12	-1	49	12	10	11	2	2	2
left AI	22	16	53	2	18	10	13	3	2	3
DMN										
right PCC	31	-40	-11	27	11	11	9	2	2	1
left PCC	27	-51	9	3	9	12	14	1	2	2
right PPC	25	-23	-45	16	12	12	14	2	2	2
left PPC	24	-41	43	7	12	10	11	2	2	2
vmPFC	21	34	-10	-22	15	15	13	3	3	2

Note: MNI = Montreal Neurological Institute, dACC = dorsal anterior cingulate cortex, dlPFC = dorsolateral prefrontal cortex, IPC = inferior parietal cortex, PCC = posterior cingulate cortex, PPC = posterior parietal cortex, vmPFC = ventromedial prefrontal cortex, AI = anterior insula, M1 = primary sensorimotor cortex, pACC = posterior anterior cingulate cortex.

Table 2.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Activations in Decibel Units for FPCN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
dACC									
Delta	.15 -.17^	-.27 .25**	.08 -.62 .22 .29*	.15 -1.12~			.15 .25^		
Theta	.04 -.40**	-.34 -.01*		.04 .83~				.07 .23^	-.03 .17 .10 .57**
Alpha			-.01 -.16 -.11 .23^					.03 -.18^	
Beta	-.04 .65~			-.04 .59~					
Low Gamma	-.01 .29~	.20 .08^		-.01 .24~				.06 -.04*	
right dlPFC									
Delta									
Theta			.19 -.26 .10 .21^						
Alpha	.04 -.21^								.09 .06 .00 .59^
Beta				-.14 .34*			-.14 .10^		
Low Gamma									
Left IPC									
Delta				.05 -.32*			.05 -.27**		
Theta			.02 -.19 -.11 .13^						
Alpha	.01 -.35^			.01 .40*					.08 .05 -.06 .30^
Beta	-.05 .21^	.11 .05^		-.05 .60~			-.05 .25**		
Low Gamma				-.02 .23*					
Right IPC									
Delta				.03 -.39**					
Theta				.03 -.18^					
Alpha	-.04 .43**			-.04 .58~			-.04 .45~		
Beta	.00 .45**			.00 .45~			.00 .27**		
Low Gamma	-.01 .18*			-.01 .20*			-01 .13*		

Note: ^ .01 > *p* > .05, * *p* < .05, ** *p* < .01, ~ *p* < .001. MW = mind wandering, dACC = dorsal anterior cingulate cortex, dlPFC = dorsolateral prefrontal cortex, IPC = inferior parietal cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 3.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Activations in Decibel Units for DAN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
Left AI									
Delta									
Theta					**-.13 .00^**				
Alpha				**-.12 .50***		**-.07 -.20** **-.17 .57***	**-.12 .26***		
Beta	**-.10 .44****			**-.10 .84~**			**-.10 .32****		
Low Gamma	**-.07 .28^**						**-.07 .29^**	**.31 -.09***	**-.05 .66** **-.07 -.09^**
Left M1									
Delta									
Theta	**-.03 -.34***						**-.03 -.24***		
Alpha	**-.09 -.68***			**-.09 .67***			**-.09 .18^**		
Beta	**-.09 .22^**			**-.09 .94~**			**-.08 .29***		
Low Gamma	**-.03 .12^**			**-.03 .21***		**-.01 .03** **-.05 .39^**			

Note: ^ .01 > *p* > .05, * *p* < .05, ** *p* < .01, ~ *p* < .001. MW = mind wandering, AI = anterior insula, M1 = primary sensorimotor cortex, pACC = posterior anterior cingulate cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 4.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Activations in Decibel Units for DMN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
left PCC									
Delta									
Theta									
Alpha	-.06 .21*	-.03 .18^	-.06 .01 -.06 .41^	-.06 .37~			-.06 .37**		
Beta	-.03 .41~			-.03 .53~			-.03 .47~		
Low Gamma	.01 .18**			.01 .23~			.01 .24*		
right PCC									
Delta									
Theta				-.10 -.41^		-.12 -.14 -.07 -.69^			
Alpha				-.09 .27**					
Beta				-.03 .37~					
Low Gamma				-.02 .31**			-.02 .18^		
left PPC									
Delta									
Theta									
Alpha				-.04 .45**					
Beta		.15 -.04^		.00 .49**					
Low Gamma		.06 -.17**		-.02 .49*					.04 .02 -.08 .81^
right PPC									
Delta									.08 -.15 -.15 .21^
Theta									
Alpha				-.07 .33**			-.07 .12^		
Beta	-.02 .52**			-.02 .52~			-.02 .23*		
Low Gamma		.11 -.05*	.02 .19 -.01 -.09^						
vmPFC									
Delta									
Theta									
Alpha			-.02 -.21 -.19 .33^	-.10 .32*			-.10 .16^		
Beta	.00 .26^			.00 .45**			.00 .16^		
Low Gamma				.11 .51*					

Note: ^ $.01 > p > .05$, * $p < .05$, ** $p < .01$, ~ $p < .001$. MW = mind wandering, PCC = posterior cingulate cortex, PPC = posterior parietal cortex, vmPFC = ventromedial prefrontal cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 5.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Correlations Between Target Electrode Pairs for FPCN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
dACC - left IPC									
Delta				.11 .31*		.04 .29 .17 .22*			
Theta									
Alpha			.25 .53 .40 .35*			.25 .38 .40 .24^			
Beta	.32 .72~								
Low Gamma	.20 .31^								
right dlPFC – left dlPFC									
Delta	.27 .42^				.43 .21*				
Theta		.58 .40*		.46 .31^	.47 .31^			.55 .32**	
Alpha		.73 .57**						.67 .57^	
Beta	.43 .71~								
Low Gamma	.27 .48**	.47 .28*			.39 .27^				
right dlPFC – right PPC									
Delta									
Theta									
Alpha		.67 .46**			.61 .47^				
Beta	.34 .57**			.34 .49*					
Low Gamma	.27 .50~			.27 .40^					
right IPC – left dlPFC									
Delta									
Theta									
Alpha		.64 .47*			.63 .44**			.59-45*	
Beta	.42 .56^								
Low Gamma	.27 .44**	.50 .22~			.41 .22**			.38 .25^	

Note: ^ .01 > p > .05, * p < .05, ** p < .01, ~ p < .001. MW = mind wandering, dACC = dorsal anterior cingulate cortex, dlPFC = dorsolateral prefrontal cortex, IPC = inferior parietal cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 6.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Correlations Between Target Electrode Pairs for DAN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
left AI – pACC									
Delta									
Theta								**.14 .21***	
Alpha	**.19 .48~**	**.42 .26***			**.30 .15^**				
Beta	**.25 .49~**	**.46 .28***							**.33 .14 .18 .32***
Low Gamma	**.14 .29***	**.31 .12****						**.24 .08***	
right AI - pACC									
Delta									
Theta									
Alpha									
Beta	**.35 .54***						**.35 .22^**		
Low Gamma	**.09 .33****			**.09 .23^**					
left AI – left M1									
Delta					**.25 .01****	**.17 .33 .12- .11***	**.15 .33***		
Theta	**.25 .41^**								
Alpha	**.27 .50****								
Beta	**.33 .57****				**.45 .31^**				
Low Gamma		**.44 .28***			**.44 .25***			**.43 .21****	
right AI – left M1									
Delta									
Theta	**.29 .49***								
Alpha	**.33 .50***								
Beta	**.31 .58~**								
Low Gamma									

Note: ^ .01 > *p* > .05, * *p* < .05, ** *p* < .01, ~ *p* < .001. MW = mind wandering, AI = anterior insula, M1 = primary sensorimotor cortex, pACC = posterior anterior cingulate cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 7.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Correlations Between Target Electrode Pairs for DMN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
vmPFC – left PCC									
Delta									
Theta							.17 .36*		
Alpha	.39 .57*								
Beta	.31 .55**	.51 .35*							
Low Gamma	.24 .37^	.38 .23*							
vmPFC – right PCC									
Delta									
Theta		.39 .52^		.49 .35^	.35 .50^		.49 .36^	.36 .49^	
Alpha									
Beta	.47 .65**			.45 .57^					
Low Gamma	.23 .45**			.23 .34^					

Note: ^ .01 > p > .05, * p < .05, ** p < .01, ~ p < .001. MW = mind wandering, PCC = posterior cingulate cortex, PPC = posterior parietal cortex, vmPFC = ventromedial prefrontal cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 8.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Correlations Between Target Electrode Pairs for FPCN - DAN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
<u>left AI – left IPC</u>									
Delta					**.37 .16***	**.24 .51** **.26 .07***			
Theta					**.50 .36^**			**.57 .39***	
Alpha	**.52 .65^**				**.57 .45^**	**.52 .62** **.53 .36^**			
Beta	**.41 .65~**	**.58 .48^**		**.41 .54***					
Low Gamma				**.23 .46****			**.23 .40***		
<u>right AI - left IPC</u>									
Delta					**.29 .03****				
Theta									
Alpha		**.48 .31***			**.47 .27****			**.46 .24****	
Beta	**.25 .61~**	**.49 .37^**						**.34 .15***	
Low Gamma					**.38 .18****				
<u>dACC - pACC</u>									
Delta									
Theta				**.26 .08^**			**.26 .07***		
Alpha	**.29 .51****	**.49 .32***						**.33 .20^**	
Beta	**.34 .67~**								
Low Gamma	**.11 .33****	**.31 .14***		**.11 .27***	**.26 .12***			**.19 .07***	
<u>dACC – left M1</u>									
Delta									
Theta									
Alpha	**.28 .47***			**.24 .41^**					
Beta	**.30 .69~**			**.30 .52****					
Low Gamma	**.20 .35***	**.35 .19***							

Note: ^ .01 > *p* > .05, * *p* < .05, ** *p* < .01, ~ *p* < .001. MW = mind wandering dACC = dorsal anterior cingulate cortex, dlPFC = dorsolateral prefrontal cortex, IPC = inferior parietal cortex, AI = anterior insula, M1 = primary sensorimotor cortex, pACC = posterior anterior cingulate cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 8 continued.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Correlations Between Target Electrode Pairs for FPCN - DAN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
right dlPFC – right AI									
Delta	.00 .26**			.00 .20*			.00 .17^		
Theta									
Alpha	.29 .42^								
Beta	.40 .66~								
Low Gamma	.17 .39**	.37 .19*		.17 .34*	.32 .18^			.27 .13^	
right dlPFC – pACC									
Delta	.16 .36*								
Theta									
Alpha	.35 .53*	.53 .35*							
Beta	.33 .62~								
Low Gamma	.13 .31*	.31 .13*		.13 .28*					

Note: ^ .01 > *p* > .05, * *p* < .05, ** *p* < .01, ~ *p* < .001. MW = mind wandering, dACC = dorsal anterior cingulate cortex, dlPFC = dorsolateral prefrontal cortex, IPC = inferior parietal cortex, AI = anterior insula, M1 = primary sensorimotor cortex, pACC = posterior anterior cingulate cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 9.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Correlations Between Target Electrode Pairs for DMN - DAN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
dACC – right PPC									
Delta									
Theta			.43 .37 .29 .39^						
Alpha		.65 .51^							
Beta	.40 .59*			.40 .55*					
Low Gamma	.40 .53^				.49 .38^	.40 .57 .40 .34^			
left AI – right PPC									
Delta									
Theta									
Alpha	.20 .40*		.16 .57 .25 .22*					.17 .31^	
Beta	.11 .43~			.11 .30*					
Low Gamma									
right AI – right PPC									
Delta	.03 .23^								
Theta						.05 .15 .24- .02^			
Alpha	.24 .40^				.35 .19^				
Beta	.19 .40*								
Low Gamma	.10 .30*			.10 .26*					
vmPFC – left M1									
Delta									
Theta		.37 .17*		.29 .10*					
Alpha	.28 .43^	.42 .29^							
Beta	.25 .63~			.25 .45**					
Low Gamma	.13 .26^	.27 .12^	.11 .43 .15 .09*	.13 .29*					

Note: ^ .01 > *p* > .05, * *p* < .05, ** *p* < .01, ~ *p* < .001. MW = mind wandering, PCC = posterior cingulate cortex, PPC = posterior parietal cortex, vmPFC = ventromedial prefrontal cortex, AI = anterior insula, M1 = primary sensorimotor cortex, pACC = posterior anterior cingulate cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 10.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Correlations Between Target Electrode Pairs for DMN - FPCN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
right IPC – right PPC									
Delta									
Theta									
Alpha	.51 .67*			.51 .70**					
Beta	.50 .64^				.61 .49^				
Low Gamma	.28 .48**	.45 .30*			.42 .19**				
vmPFC - dACC									
Delta		.27 .48*							
Theta		.42 .58^			.38 .59*			.46 .61^	
Alpha	.69 .83*								
Beta	.60 .78**			.60 .71*					
Low Gamma									
left PCC - dACC									
Delta									
Theta									
Alpha			.46 .69 .59 .51^						
Beta	.35 .57**	.54 .39^							
Low Gamma					.41 .27*	.33 .41 .30 .27^			
right PCC - dACC									
Delta	.17 .38*								
Theta									
Alpha	.43 .59*	.58 .44^						.48 .35^	
Beta	*.40 .62*			.40 .52^					
Low Gamma	.18 .43~			.18 .35**	.32 .21^			.26 .13*	

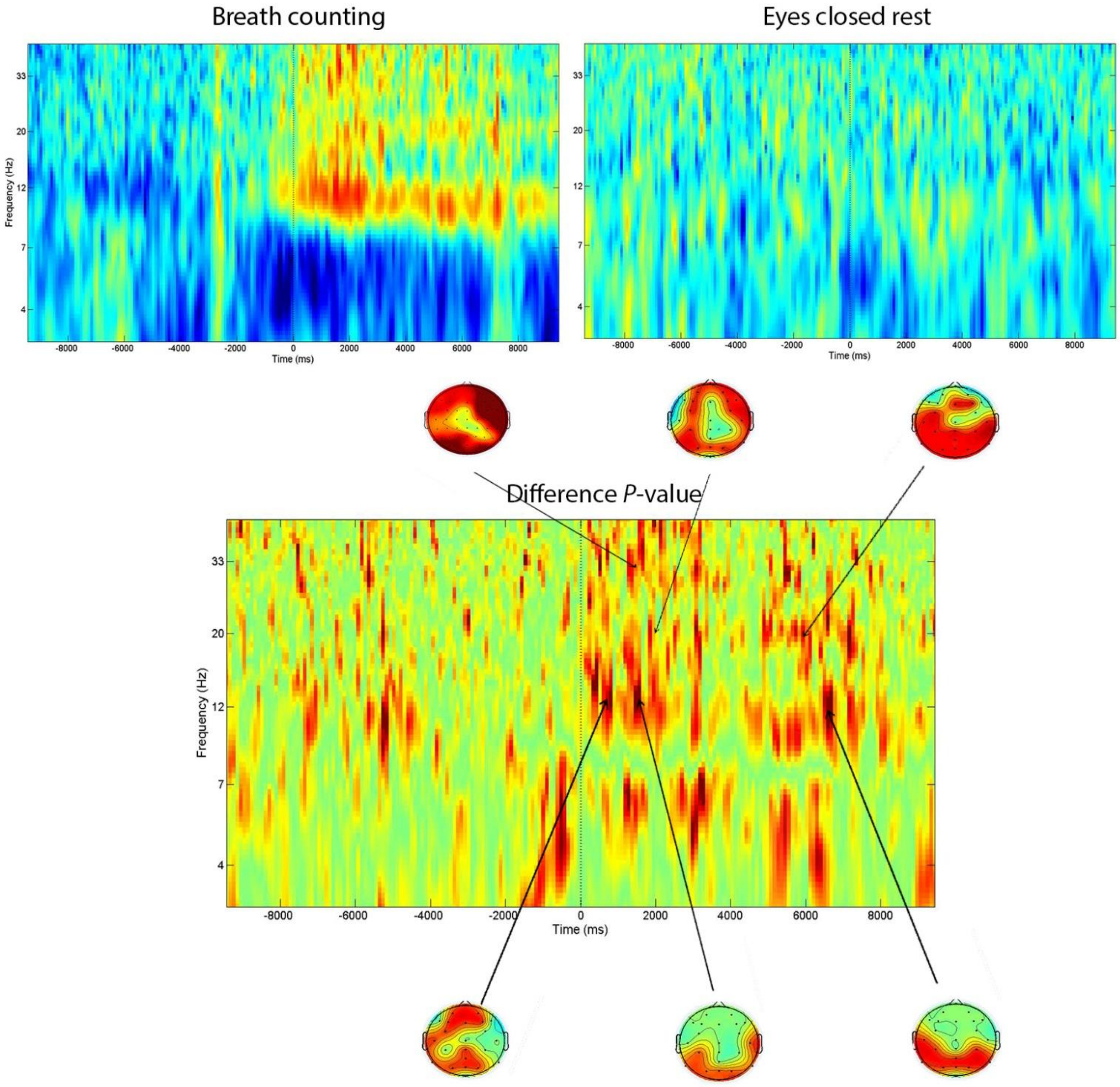
Note: ^ .01 > *p* > .05, * *p* < .05, ** *p* < .01, ~ *p* < .001. MW = mind wandering, dACC = dorsal anterior cingulate cortex, dlPFC = dorsolateral prefrontal cortex, IPC = inferior parietal cortex, PCC = posterior cingulate cortex, PPC = posterior parietal cortex, vmPFC = ventromedial prefrontal cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).

Table 10 continued.

Results from Separate 2 X 2 Mixed Factorial ANOVAs Comparing Average Frequency Band Correlations Between Target Electrode Pairs for DMN - FPCN Nodes Between the Time Epoch of MW(first number in each cell) and the Epochs of Aware, Shift, and Focus (second number in each cell).

	MW vs. Aware			MW vs. Shift			MW vs Focus		
	Time	Group	G x T	Time	Group	G x T	Time	Group	G x T
vmPFC – left IPC									
Delta									
Theta									
Alpha						**.25 .44** **.34 .25^**			
Beta	**.22 .63~**			**.22 .37^**					
Low Gamma									
vmPFC – right IPC									
Delta		**.24 .44***							
Theta									
Alpha									
Beta	**.42 .62****			**.42 .55^**					
Low Gamma	**.27 .46****	**.46 .28****			**.38 .26^**				
vmPFC – left dlPFC									
Delta									
Theta									
Alpha									
Beta	**.52 .72****								
Low Gamma	**.30 .44^**	**.44 .31^**							
vmPFC – right dlPFC									
Delta									
Theta									
Alpha				**.60 .72^**					
Beta	**.46 .71~**			**.46 .60***					
Low Gamma	**.29 .49****								

Note: ^ .01 > p > .05, * p < .05, ** p < .01, ~ p < .001. MW = mind wandering, dACC = dorsal anterior cingulate cortex, dlPFC = dorsolateral prefrontal cortex, IPC = inferior parietal cortex , PCC = posterior cingulate cortex, PPC = posterior parietal cortex, vmPFC = ventromedial prefrontal cortex. Results in bordered boxes are replications from Hasenkamp et al. (2011).



Breath counting

Eyes closed rest

Difference *P*-value

Figure 1. From Fix & Faust (2017) depicting time-frequency maps and scalp topographies surrounding button presses and the *p*-values (bottom) of the independent samples *t*-tests comparing BC (left) and eyes closed rest (right) at site Oz.

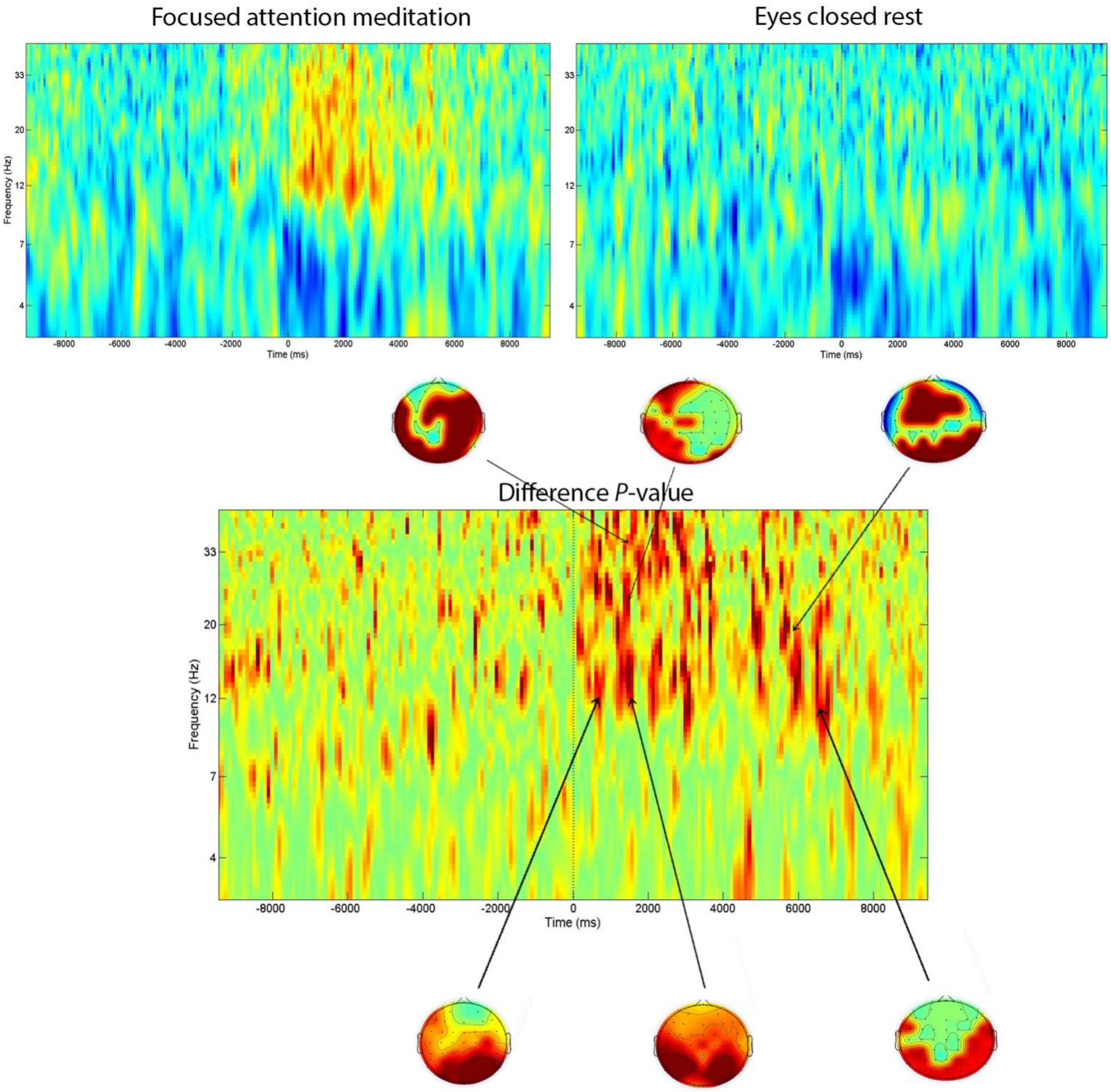


Figure 2. From Fix & Faust (2017) depicting time-frequency maps and scalp topographies surrounding button presses and the *p*-values (bottom) of the independent samples *t*-tests comparing FAM (left) and eyes closed rest (right) at site Oz.

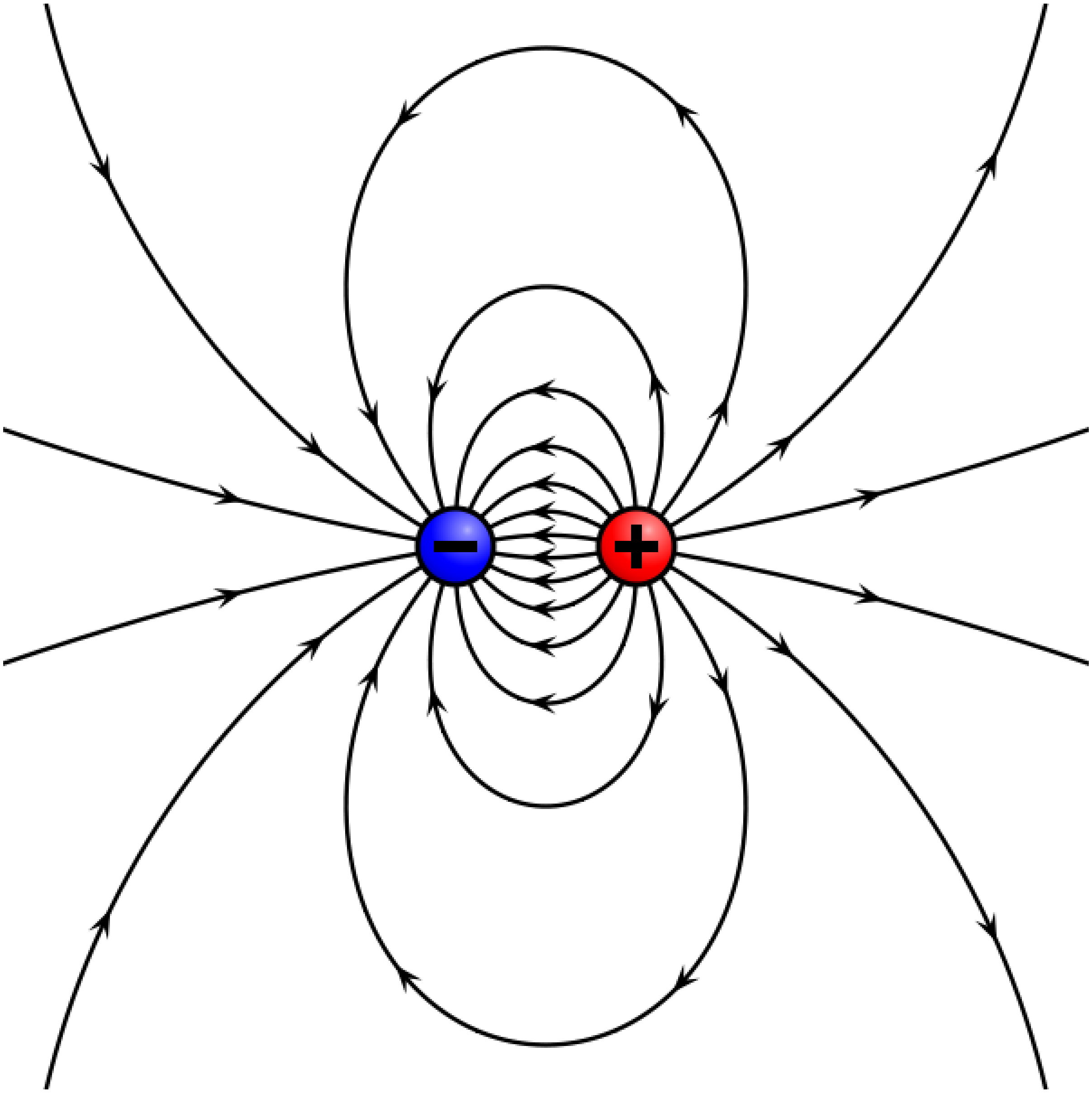


Figure 3. Depiction of electrical activity surrounding a dipole source generator.

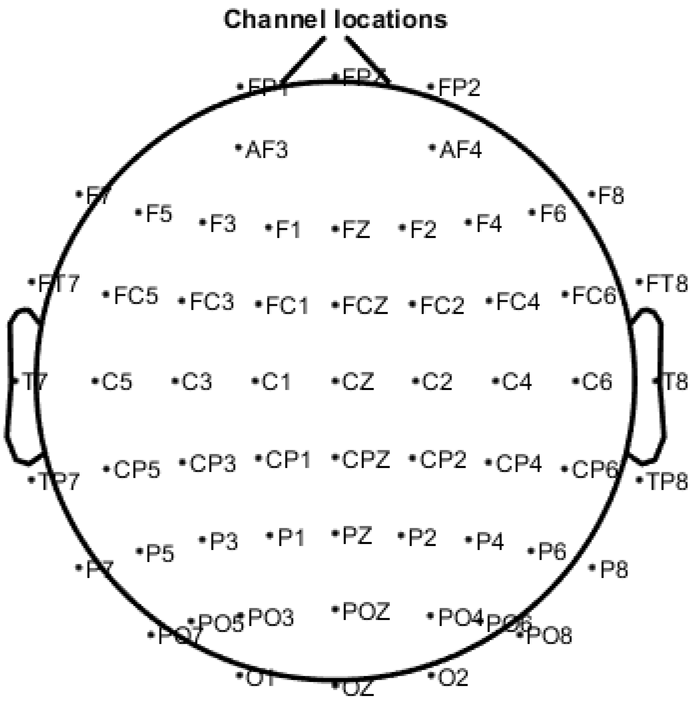


Figure 4. Electrode locations relative to a boundary element head model.

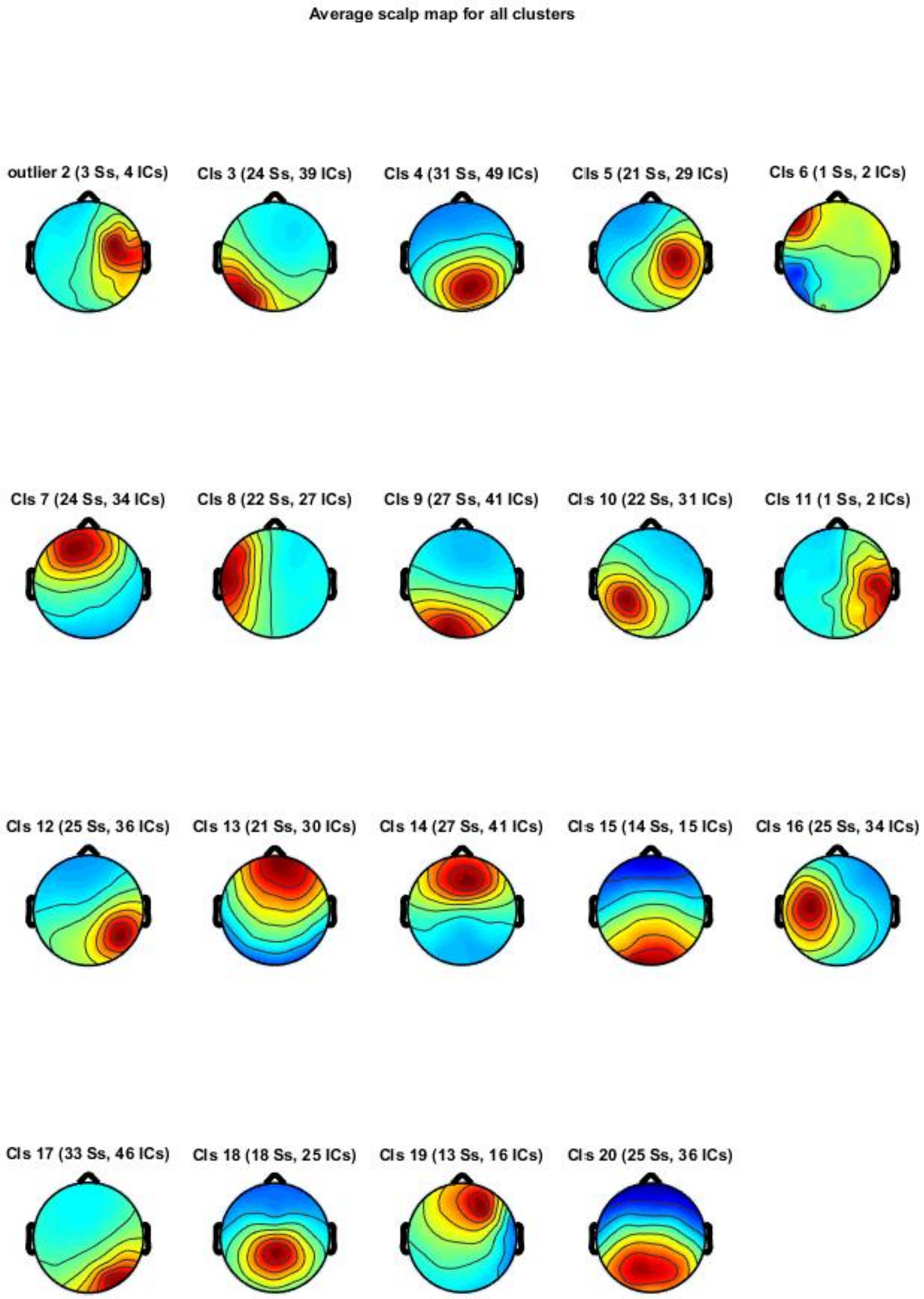


Figure 5. Scalp maps of all 19 clusters identified with sICA.

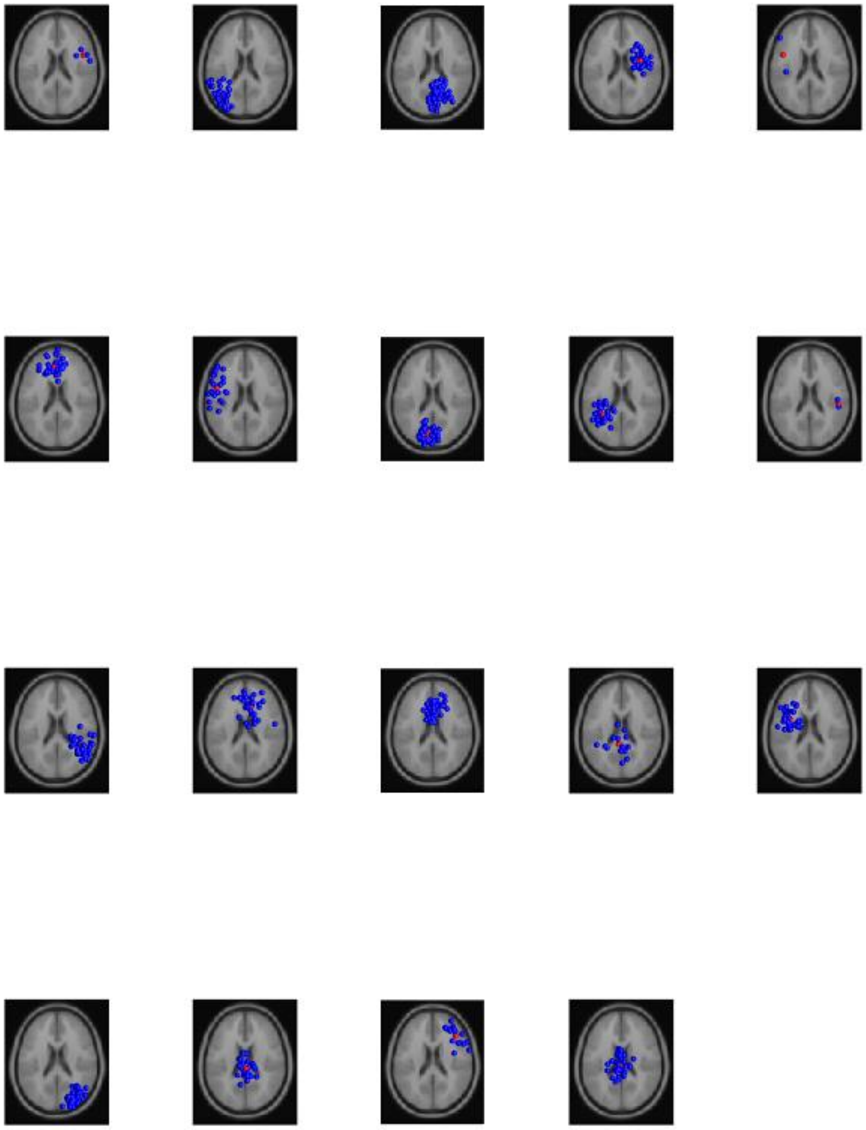


Figure 6. 3D dipole locations of all 19 clusters identified with sICA and modeled with the DIPFIT2 plugin for EEGLAB.

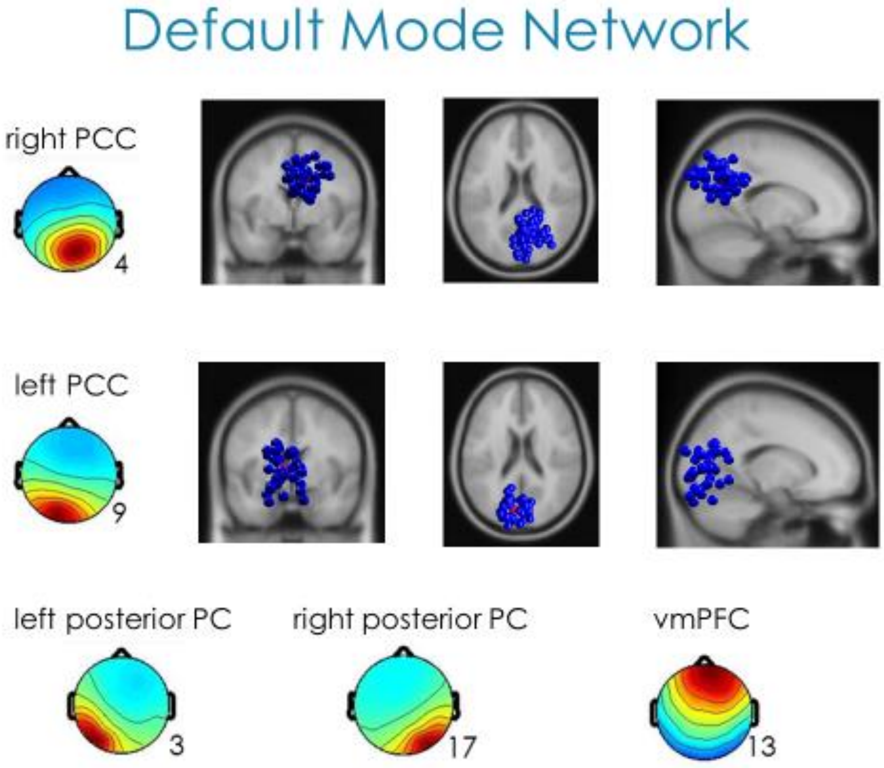


Figure 7. Summary illustrations for major hubs of the DMN, including cluster scalp maps and 3D dipole locations.

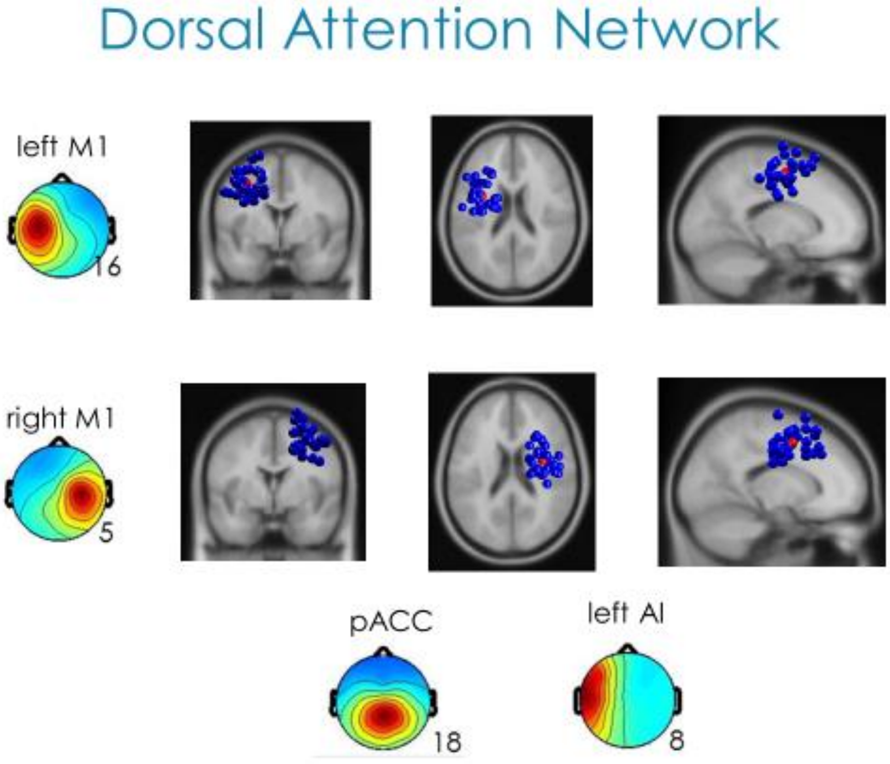


Figure 8. Summary illustrations for major hubs of the DAN, including cluster scalp maps and 3D dipole locations.

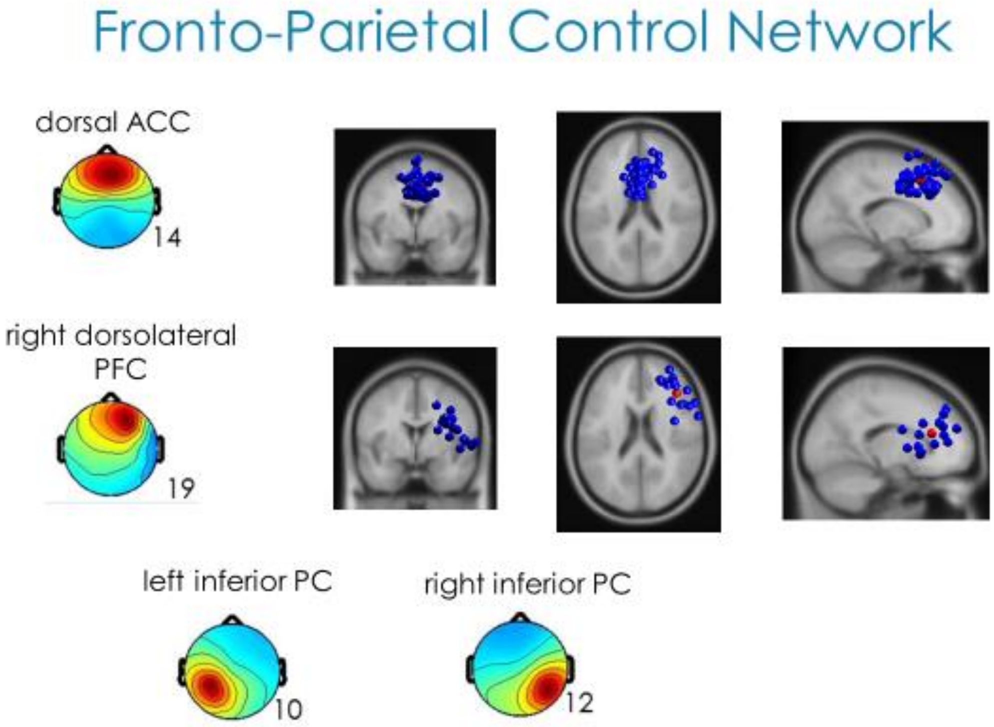


Figure 9. Summary illustrations for major hubs of the FPCN, including cluster scalp maps and 3D dipole locations.

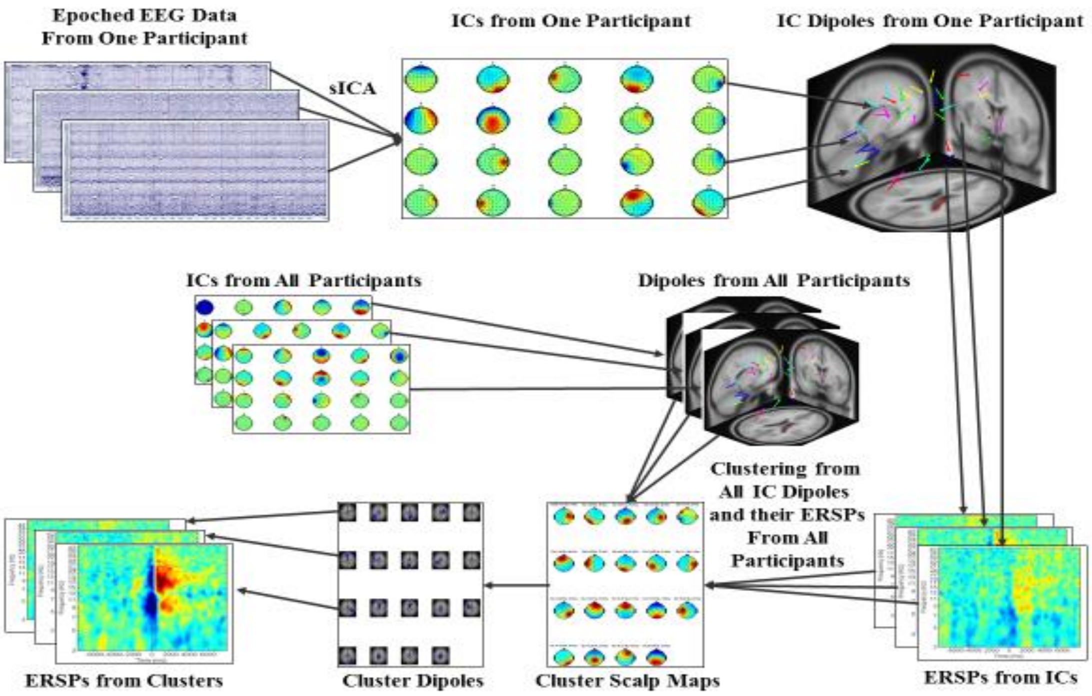


Figure 10. Conceptual diagram of epoched EEG data being submitted to sICA, dipole source modeling, and ERSP analysis for each participant, along with subsequent IC clustering across participants to generate ERSPs from group IC clusters.

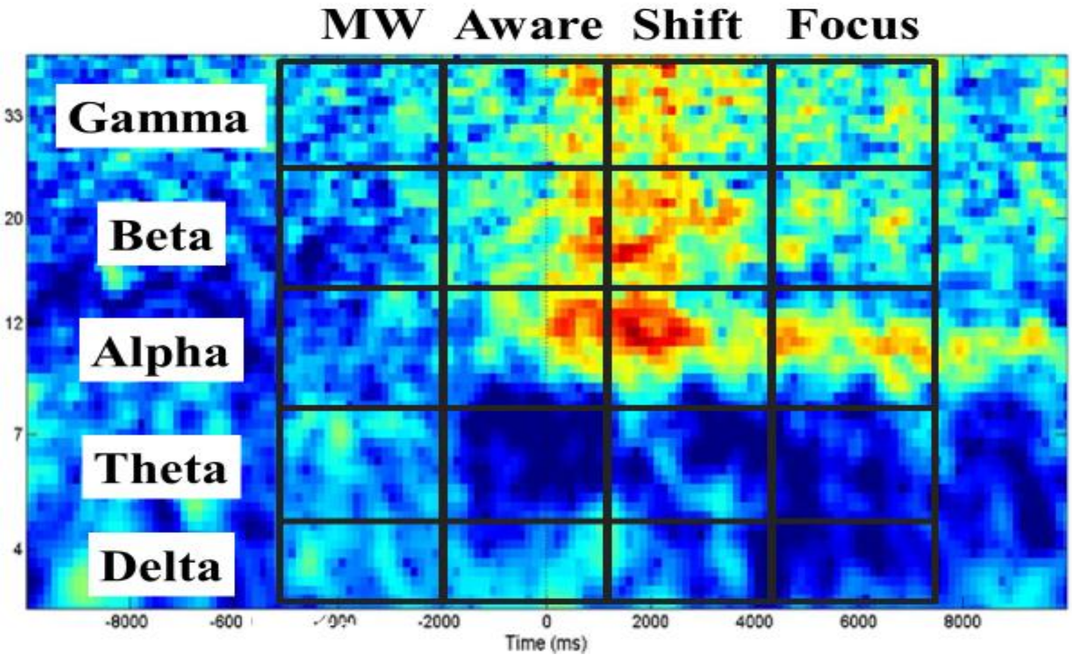


Figure 11. Illustration of the frequency band by time epoch windows that were used to reduce ERSP data. Average ERSP data within each window were used in all subsequent analyses.