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IMPACT OF SHORT MEDITATION ON ATTENTIONAL PERFORMANCE

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IMPACT OF SHORT MEDITATION ON ATTENTIONAL PERFORMANCE

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Arts and Sciences
at the University of Kentucky

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ABSTRACT OF DISSERTATION

IMPACT OF SHORT MEDITATION ON ATTENTIONAL PERFORMANCE

Meditation describes a large variety of traditions that all include the conscious focus of attention. By maintaining attention, meditators experience both acute and long-term changes in physiology, anatomy, and cognitive performance. The type of performance benefit is believed to depend, at least in part, on the specific type of mental training. What is much less clear in the literature is the impact of a single session of meditation on the brain and how the acute changes could impact performance. Studies in advanced meditators show an increase in neuronal coordination and slowing of neuronal firing across many regions in the brain, but this remains poorly studied in novices. It is also unknown how neural dynamics fluctuate over time during meditation, as most studies have assumed the changes remain relatively constant.

To investigate this, non-meditators were taught a simple eyes-closed focused breathing meditation. This technique is common to many meditation traditions and is often used at the start or end of more advanced meditation techniques. Using a within subject design, attention and vigilance were measured using the psychomotor vigilance test (PVT). Novice meditators showed improvement on the PVT with 20 minutes, and even 5-minutes of meditation in a large classroom setting.

Using electroencephalography, EEG, the neural dynamics during a single session of 20-minute meditation were investigated. This exploratory analysis also implemented a phase synchronization measure of coherence, mean phase coherence (MPC), which is novel to the meditation field. Results suggest that MPC may have identified regions of high coherence during meditation that are also correlated with improved PVT attentional performance. The results also suggest that meditation is a dynamic neural process that requires more careful analysis into changes over time (across a single meditation bout). Finally, results suggest that "control" conditions need to be more systematically studied, as many conditions may show similar benefits or neural dynamics to meditation.

KEYWORDS: Meditation, attention, performance, EEG, neural dynamics, mean phase coherence

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IMPACT OF SHORT MEDITATION ON ATTENTIONAL PERFORMANCE

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DEDICATION

To Grandma Riek, Aunt Debbie, Grandpa Guerriero, and Nana. You weren’t able to see this day, but your love helped me achieve a great many things.

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CHAPTER 1. INTRODUCTION

Meditation is the conscious control of attention. While this is a broad concept, particularly in how it is used in many cultural traditions, all forms of meditation involve manipulating the state of mind and regulating internal attention (C. Kaur & P. Singh, 2015). Some of the earliest texts describing meditation appear in the Upanishads, which are believed to be written between 900-500 BCE (Subramanya & Telles, 2009). Since that time almost all major religions have developed some form of meditation. This mental training has become widespread outside of religious traditions and is used for self-actualization, stress reduction, and improving mental well-being (Lee et al., 2018).

Meditative practices can be generally categorized into two groups: focused attention and open monitoring (C. Kaur & P. Singh, 2015; Lee et al., 2018; Travis & Shear, 2010). Concentrative or focused attention meditations (FA) rely on focusing on a single "object," such as "the breath", a single word, or a mantra. In contrast, open monitoring (OM), or mindfulness meditations, do not focus on any single stimulus or experience; instead, the intention is to monitor thoughts as they come without passing judgment.

However, not all meditation researchers use these two categories. Some researchers consider it too simplistic in categorizing the wide variety of meditation traditions. Travis and Shear argue that transcendental meditation (TM), a meditative practice that involves automatic self-transcending, belongs in a third distinct category (Travis & Shear, 2010). Further, "loving kindness" meditation, which focuses on developing love and kindness toward the self and then extending to others, combines elements of both FA and OM (Dominique P Lippelt et al., 2014).

1. Early Meditation Research – 1960s and 70s

Meditation research initially became popular in the 1960s and 1970s when researchers studied the physiology of yogis, practitioners of Transcendental meditation (TM), and mindfulness meditators. Yoga consists of a wide variety of religious and philosophical traditions spanning many centuries in India, with meditative practices focusing on inner peace or enlightenment achieved in part by reducing distractions from internal or external stimuli (Aftanas & Golocheikine, 2001). Transcendental meditation (TM), a type of FA meditation focuses on a mantra/sound with the intent to experience transcendental consciousness (Travis et al., 2002).

While technologically limited, these early studies laid an important groundwork in our current understanding of meditation-induced physiological changes. The findings indicated that meditation induces a hypometabolic state; meditators had slower respiration rates, decreased galvanic skin responses, and reduced heart rates than non-meditators (Bagchi, 1958; Kasamatsu & Hirai, 1966; Wallace, 1970). TM and other FA meditations also induce a hypometabolic state during practice as compared to rest (Benson et al., 1975; Elson et al., 1977; Morse et al., 1977). These physiologic changes were attributed to decreased sympathetic nervous system activation (Davidson, 1976; Lang et al., 1979) and increased parasympathetic activation (Bujatti & Biederer, 1976). However, other studies found no such change – or even opposite changes with heart rate and respiration (Das, 1957). These conflicting results have been attributed to the variability in types of meditation practices and difference in experimental designs and types of subjects. Still, recent research is likewise inconclusive: some show decreased sympathetic activity (Walton et al., 1995; Young & Taylor, 1998) and increased parasympathetic activity (Kubota et al., 2001; Young & Taylor, 1998), others show no impact on autonomic activity (using heart rate variability, (Takahashi et al., 2005).

1.1.1 Early EEG studies of meditation

These early studies relied on electroencephalography (EEG) to study neural dynamics, a way to record electrical activity of the human brain non-invasively (İnce et al., 2020). By placing electrodes on a person's scalp, EEG can measure changes in electrical current that indicate changes in the activity of brain synapses, providing results in the form of electric potentials (Teplan, 2002). The currents detected by EEG are mostly due to the dendritic excitation of pyramidal neurons in the cerebral cortex. This is because the pyramidal neurons are close to the measurement electrodes and their signal masks other electrical activity. Thus, deeper neuronal dynamics are not measured by EEG (Teplan, 2002).

To quantify wave magnitudes, EEG data is Fourier transformed to determine the power spectrum at these different frequencies (Teplan, 2002). Although the exact frequency intervals vary based on definition, the waves are defined as: delta (0.5-3 Hz or 1/sec), theta (3-7 Hz), alpha (7-13 Hz), beta (13-30 Hz), and gamma (>30 Hz) (slowest to fastest). Contributions of all waves are seen in all EEG at all times, but the relative amounts of these change during different activities (Teplan, 2002). The first "brain wave" identified in humans was the Berger wave, or alpha wave, which becomes more prominent when the eyes are closed (Barry et al., 2007; İnce et al., 2020). We now understand the alpha eye-closed wave to be due to the ocular cortex/ occipital cortex not receiving any visual signals and a synchronization of neurons at this frequency (Barry et al., 2007).

EEG studies during the 1960s and 1970s showed that experienced meditators had different neurophysiology compared to non-meditators. Specifically, meditation showed a slowing of cortical activity – moving from the faster beta waves common while awake to the slower alpha and theta rhythms (Anand, 1961; Banquet, 1973; Kasamatsu & Hirai, 1966; Wallace, 1970). Further, some tradition-specific patterns emerged. During meditation, Samadhi yogis were found to have higher alpha waves (compared to other meditators, (Anand, 1961); Buddhist Zen meditators showed alpha waves in the frontal and central cortical regions and theta wave transient bursts after 20 minutes of practice (compared to non-meditator controls, (Kasamatsu & Hirai, 1966); and transcendental meditation increased gamma power, specifically at 40 Hz (compared to non-meditator controls, (Banquet, 1973).

It is important to note that EEG measurements common in these early studies have several limitations. Because individual neurons produce undetectably small electric potentials, EEGs can detect only the summed activity of many neurons at a threshold still detectable through the scalp, skull, and meninges (Teplan, 2002). Still, though these early studies lacked spatial information due to use of few electrodes and computational limitations, they have been replicated and more completely characterized using modern technology and mathematical algorithms (see Section 2.2).

1.1.2 Impact of meditation on performance

Though changes in neurophysiology were not systematically studied in relation to performance and anxiety, a few studies documented differences in performance between meditators and nonmeditators. These studies found differences primarily with transcendental meditation (TM); TM meditators showed faster reaction times than non-meditators (Appelle & Oswald, 1974) and compared to a pre-meditation baseline (Holt et al., 1978). There were also occasional reports of exceptional abilities in these long-term meditators. Anand, Chhina, and Singh (Anand, 1961) reported that a subset of their yogi subjects were more resistant to pain induced by putting one's hand in cold water for 45-55 min.. This finding was supported by recent research documenting reduced brain activation in response to painful hot water (Orme-Johnson et al., 2006). Other studies have documented an effect of meditation on anxiety. Experienced meditators habituated quickly to distracting and stressful stimuli (Anand, 1961; Goleman & Schwartz, 1976; Orme-Johnson et al., 2006; Puryear et al., 1976), and newly-trained meditators self-reported lower levels of anxiety after training (Puryear et al., 1976; Wallace & Benson, 1972).

2. The current field of meditation research – 1980s to now

Meditation research has gained popularity since the 1960s and 70s, and the results indicate a positive effect of meditation on general health and wellbeing. Clinical studies indicate reduced insomnia, attention deficit hyperactivity disorder, anxiety disorders, and hypertension (Janssen et al., 2015; King et al., 2002; Miller et al., 1995; Mitchell et al., 2017; Walton et al., 1995; Zylowska et al., 2008). One study suggests it elongates life (Alexander et al., 1989). However, these studies document correlations only and lack investigation into the processes involved in meditation and how they interact with normal or abnormal physiology.

Improvements in technology and physiological understanding have led to improved methodologies in meditation research. Because EEG can gather data at a very high temporal resolution, it is still commonly used. However, modern technology allows EEGs to distinguish neural dynamics at much higher spatial resolution (Dissanayaka et al., 2015) (Section 2.2). Further, results from EEGs have been combined with results using other kinds of technology, namely functional magnetic resonance imaging (fMRI). fMRI shows changes in blood flow of the brain and is interpreted under the assumption that brain regions with more blood flow are more active (Hasenkamp et al., 2012; Lazar et al., 2000; Takahashi et al., 2005) (Section 2.1). Thus, while EEG measures mostly cortical changes, fMRI also shows the activity of deep brain regions.

1.1.3 Functional Magnetic Resonance Imaging (fMRI) Studies of Meditation

fMRI studies have identified both cortical and deep structures active during meditation. Specifically, both FA and OM meditation activate the prefrontal cortex and parietal cortex (Froeliger et al., 2012; Hasenkamp et al., 2012; Lazar et al., 2000; Takahashi et al., 2005), which are attention regulation regions of the brain. This may be because both subtypes involve self-regulation and the conscious control of attention (Lazar et al., 2000; D. P. Lippelt et al., 2014; Manna et al., 2010). However, another hypothesis is that meditation changes the activation of the default mode network (DMN). The DMN is most active during passive rest or involuntary activities and is thus less active during behaviors that require executive control (Lee et al., 2018; Travis & Parim, 2017). A few studies have found that meditation experience reduces the DMN activation (Brewer et al., 2011, Simon & Engstrom, 2015). However, this is still unclear, as there is fMRI evidence that DMN activation is due to mind wandering instead of meditation (Hasenkamp et al., 2012).

Like EEG, fMRI research has limitations. One is that fMRI gathers data at a much slower rate than EEG; for example, meditation dynamics have been sampled by fMRI at

33Hz (Hasenkamp et al., 2012; Lazar et al., 2000), whereas EEG samples at 128 Hz or faster (Kopal et al., 2014; Lo & Chang, 2013; Tomljenović et al., 2016; Travis & Parim, 2017) (up to 5kHz (Dissanayaka et al., 2015)). EEG studies have better temporal resolution which helps understand meditation-associated temporal dynamics and cortical changes, thereby providing information about how cortical neurons may be communicating or coordinating across cortical regions.

1.1.4 EEG Studies of Meditation

All the changes induced by meditation can be broken into two categories based on the length of their impact. State changes is the term given to short-term changes that take place during or after meditation practice. In contrast, trait changes are the more permanent changes in response to extensive meditation practice and frequent repetition of the same attentional processes.

1.1.4.1 State Changes due to Meditation

State changes can be most easily studied in novice meditators. Their lack of meditation experience means they have no long-term trait changes that could influence the brain and their resulting performance. Therefore, any changes observed after meditation cannot by definition be classified as a long-term effect. State effects of meditation are directly due to changes in variable neuronal activity, specifically measured as changes in neuronal speed (power) and neuronal coordination (coherence).

1.1.4.1.1 Neuronal Speed – Power of Frequency Waves

Neural oscillations are the rhythmic patterns of neural activity and are measured in frequency (using Hz or 1/sec). Measured using EEGs, neuronal speed, which is also referred to as firing, can be detected as changes in voltage across the scalp (Teplan, 2002) which is reported as power, or magnitude, of the different frequency waves (Ng et al., 2012); see section 1.1). In general, modern EEG studies support the earlier findings: meditation acutely causes slowing of neuronal frequency by increasing the power of alpha and theta waves (see below), which is interpreted as neuronal slowing from the dominant beta wave of normal wake (Teplan, 2002). This increase in power is caused by increased neurons firing in this frequency range.

The frontal lobe of the cortex is responsible for executive controls, including attention regulation, working memory, and emotional regulation (Aftanas & Golocheikine, 2001; Klimesch, 1999). EEG studies showed that neural dynamics in the frontal lobe changes in response to meditation. This is likely due to the attention regulation and executive control used during meditation practices. Most studies of focused attention (FA) meditation show an increase in EEG alpha power in the frontal lobe (approximately 8 to 12 Hz, depending on the definition used by the authors) (Banquet, 1973; Cahn & Polich, 2013; Dunn et al., 1999; Klimesch et al., 1996; Takahashi et al., 2005) and has been associated with increased relaxation and attention (Aftanas & Golocheikine, 2001; Cahn & Polich, 2013). Other studies have documented meditators with even slower neuronal firing in the frontal cortex into lower alpha (8-10 Hz) and the theta range (4 to 8 Hz) (compared to pre-meditation control baseline; (Aftanas & Golocheikine, 2001; Banquet, 1973; Cahn et al., 2010; Lee et al., 2018; Mizuki et al., 1980; Takahashi et al., 2005). The power and location of these slow alpha and theta waves is similar to that which takes place during attention tasks (Kubota et al., 2001), complex cognitive tasks (Mizuhara et al., 2004), and during consciousness and sensory perception (Kjaer et al., 2002).

Other non-meditation attention-regulating tasks have shown similar neural dynamics as those reported during meditation. The increases in alpha power in the frontal cortex have been documented during simple, paced breathing with eyes open while counting and using non-meditator subjects (Fumoto et al., 2004; Stancák et al., 1993). This paced breathing task is based on counting. Fumoto and colleagues designed their breathing task be distinct from meditation by the authors and non-meditator subjects were chosen (Fumoto et al., 2004; Stancák et al., 1993). Stančák and colleagues studied paced breathing as a way to change cardiovascular measures (Stancák et al., 1993). These studies indicating that breathing control can increase EEG frontal alpha power outside of formal meditation, suggesting that the "attention to breathing" that is common to many subtypes of meditation and early meditation training induces physiological changes that can be induced separately from religious, mystic, or purposes of self-actualization.

Meditation could also impact the neural dynamics in the occipital lobe. When eyes close, the occipital lobe stops receiving visual signals and enters a "default" state, waiting for visual signals. During any eyes-closed meditation practice, the occipital alpha power increase is immediately apparent (Cantero et al., 2002; Fumoto et al., 2004; Schürmann & Başar, 2001). Thus, meditative practices that include closing eyes fully or partially, common in most types, induces an increase in alpha power in the occipital lobe (Cantero et al., 2002; Park & Park, 2012; Schürmann & Başar, 2001). However, these changes may depend on meditation type; another study found no difference in occipital power of any frequency between their focused-breathing counting Zen meditation and the eyes open control condition (Takahashi et al., 2005).

A limit of current understanding of power dynamics is the temporal changes over the duration of the meditative practice. While one study found no significant changes in frontal, central, and parietal lobe alpha power over time in expert TM meditators (Travis & Wallace, 1999), another study of paced breathing found alpha quicken and increase in amplitude five minutes into the breathing exercise (Fumoto et al., 2004). However, changes in EEG power over time are rarely studied, with many papers citing Travis and Wallace (1999), which found no significant changes in frontal, central, and parietal alpha power over time in expert TM meditators (Travis & Wallace, 1999).

1.1.5 Neuronal Coordination – Coherence

Neuronal coordination is the degree to which regions of the brain are synchronized and is interpreted as a measure of functional connectivity. It is measured by the degree of correlation between two signals as a function of frequency components (Dissanayaka et al., 2015) and is reported in EEG as the amount of coherence in a frequency band, such that higher coherence indicates more communication between cortical regions (Basharpoor et al., 2021; Thatcher, 2012).

In the meditation literature, coherence has been calculated in multiple ways, making cross-study comparisons difficult and overall trends ambiguous (Table 1.1). The most common method, the Fast Fourier Transfer (FFT), calculates coherence as the concurrent changes in power using a cross-correlation between electrodes at the same time (Tomljenović et al., 2016; Travis et al., 2010; Travis et al., 2017). However, this method is unable to incorporate wave phase, or the different portions of the sinusoidal wave. For example, neurons firing at different points in the wave can have the same power and same frequency, but, because of phase differences, are unlikely to be synchronized or receiving excitation from the same neural source (Fries, 2015). Further, the FFT cross-correlation method removes sources of variation in the data by first binning the data together to calculate power; only then is coherence determined using a cross-correlation.

Most studies of coherence show that meditators have higher EEG coherence than non-meditators (Figure 1.1A), or there is more coherence during meditation practice compared to non-meditation (Figure 1.1B). This is broadly reported between the frontal cortices or between the frontal and parietal regions in focused attention (FA), open monitoring (OM), and transcendental meditations (TM) (Cahn & Polich, 2013; Travis & Parim, 2017; Travis & Shear, 2010). For example, studies on FA meditation show increased coherence between the prefrontal and posterior association regions (Aftanas & Golocheikine, 2001; Aftanas & Golosheikin, 2003) which are associated with working memory (Klimesch, 1999; Sarnthein et al., 1998) and learning (Laukka et al., 1995), respectively. Studies on OM practices indicate coherence of slower frequencies and increased theta coherence between the frontal and parietal lobes (Cahn & Polich, 2013; Lee et al., 2018). Table 1 provides further details on all EEG coherence studies in meditation.

Table 1: EEG Coherence in Meditation Studies

Citation	Meditation Type	Subjects Meditation Experience (Novice - no training, Beginner = <6 months)	Meditation Duration (mins)	Analysis Method	Coherence Findings	Notes
Dillbeck and Bronson, 1981	TM	Beginner	15	Linear coherence	TM session had increase in frontal alpha (8-12 Hz) coherence. No difference between meditators and controls.	
Orme-Johnson and Haynes, 1981	TM	Expert	20	Coherence spectral arrays (COSPARS)	Those with clear experiences of "pure consciousness" had higher alpha (8-12 Hz) coherence than those not reporting these experiences, especially in electrodes F4-C4.	The coherence variables only accounted for 50% of individual differences.
Gaylord et al., 1989	TM	Novice	20	FFT correlation	TM group had increase in global EEG coherence (ranges from 4 to 25 Hz) compared during eyes closed resting.	
Newandee and Reisman, 1996	TM individually	Novice and Experts	5	unclear	All experienced meditators show alpha (8-12 Hz) coherence above .95 with eyes opened, this was maintained or increased with eyes closed.	
	TM in groups	Novice and Experts	5	unclear	During group meditation, subjects showed more alpha and theta (4-8 Hz) coherence and less delta (0-4 Hz) as compared to eyes closed rest. EEG coherence was higher during group meditation than individual.	
Travis and Wallace, 1999	TM	Expert	10	FFT correlation	Higher alpha coherence during TM than rest in frontal, left anterior to posterior, and right anterior to posterior.	Frequency not specified
Travis, 2001	TM	Expert	16	unclear	TM subjects show higher coherence (at individual peaks in 6-12 Hz) during transcending times than at other times during meditation. TM's coherence was highest in frontal and lowest in central-parietal.	
Aftanas and Golocheikine, 2001	Sahaja Yoga	Beginner	not stated	FFT correlation	Beginners saw less alpha2 coherence in parietal, parietal/temporal, and occipital regions due to meditation compared to rest.	Frequencies based on individual alpha frequencies
		Expert	not stated	FFT correlation	Beginners showed increased theta coherence in prefrontal and posterior association cortex with some increase left prefrontal.	
Aftanas and Golocheikine, 2003	Sahaja Yoga	Beginners and Experts	not stated	FFT correlation	Experts had increase in short and long-distance theta coherence, centered in the left prefrontal region (electrode AF3). Experts had small decrease in intra- and interhemispheric coherence in posterior cortical regions.	Frequencies based on individual alpha frequencies
Lutz et al., 2004	Tibetan Nyingmapa and Kagyupa	Novice and Experts	3	Instantaneous phase	Meditators had higher gamma (25-42 Hz) coherence and larger regions of coherence during meditation than rest, and higher than controls.	Gamma (25-42 Hz) coherence was correlated with amount of experience.
Murata et al., 2004	Zen Su-Soku	Novice	15	FFT correlation	Meditation had higher alpha1 (8.2-9.77 Hz) coherence than rest in electrodes F3-F4	

Notes: TM = transcendental meditation, Hz = hertz or 1/sec, FA = focused attention, OM = Open Monitoring, FFT = Fast Fourier Transform, MVDR = Minimum variance distortion response

Areas are shaded that show meditation has less coherence than during rest.

Table 1: EEG Coherence in Meditation Studies (continued)

Citation	**Meditation Type**	**Subjects Meditation Experience (Novice - no training, Beginner = <6 months)**	**Meditation Duration (mins)**	**Analysis Method**	**Coherence Findings**	**Notes**
Travis and Arenander, 2006	TM	Beginner and Expert	10	FFT correlation	Meditators had higher frontal alpha (8-13 Hz) EEG coherence than beginners.	
		Beginner	10	FFT correlation	TM practice induces more frontal broadband coherence (6-45 Hz) during meditation than rest. This was increased from before meditation training and plateaued after 2 months of training.	
Baijal and Srinivasa, 2009	Sahaja Samadhi, Sudarshan kriya yoga	Novice and Experts	12-18	Absolute power correlation	Higher theta coherence in meditators compared to novices, especially in left frontal.	
Chan et al., 2011	Shaolin Dan Tian Breathing	Beginner	5 during passive breathing, 5 during active breathing	Absolute power correlation	Active breathing had higher theta (3-7 Hz) coherence across the electrode pairs within and between hemispheres. Passive breathing enhanced temporal alpha (8-13 Hz) asymmetry	
Travis, 2011	TM, TM-Sidhi	Expert	10 of TM, then 10 mins of TM-Sidhi	FFT correlation	No significant differences between TM and TM-Sidhi, or before meditation	
Lehmann et al., 2012	Tibetan Buddhist, QiGong, Sahaja Yoga, Ananda Marga Yoga, Zen	Expert	20 for most, 60 for Zen	Complex valued coherence, intracortical lagged coherence	All meditation types showed lower intracortical coherence than rest, especially prominent in delta* (1.5-6) and beta2 (18.5-21). Complex valued coherence also showed lower coherence during meditation than during rest across all frequencies	*Delta band overlaps with more commonly defined theta frequencies
Dissanayaka et al., 2013	Not specified	Expert	15	MVDR coherence, FFT correlation	Meditation, compared to baseline, had increased theta (4-8 Hz) coherence in frontal and central with reduced theta coherence in parietal occipital areas.	
Kopal et al., 2014	Buddhist samatha-vipassana	Expert	30 of FA breathing, 30 of insight OM	Complex continuous wavelet coherence	Broad band coherence during OM showed more distant coherence connections than the focused breathing. Higher magnitude alpha and beta coherence in OM and FA breathing than compared to controls.	Frequency not specified
Tomljenovic et al., 2016	TM	Beginner	During rest	FFT correlation	TM had increase in high alpha (8-10 Hz) and theta (4-8 Hz) coherence for central, temporal, and occipital areas compared to baseline	
Travis, Parim, and Shrivastava, 2017	TM with Vedic recitation	Experts	15 min TM, 1 hour Vedic recitation	FFT correlation	Coherence listening to Vedic recitation was higher in theta 2 (5-7 Hz) and alpha 1 (7.5-10.5 Hz) in the frontal and parietal regions than just TM.	

Notes: TM = transcendental meditation, Hz = hertz or 1/sec, FA = focused attention, OM = Open Monitoring, FFT = Fast Fourier Transform, MVDR = Minimum variance distortion response

Areas are shaded that show meditation has less coherence than during rest.

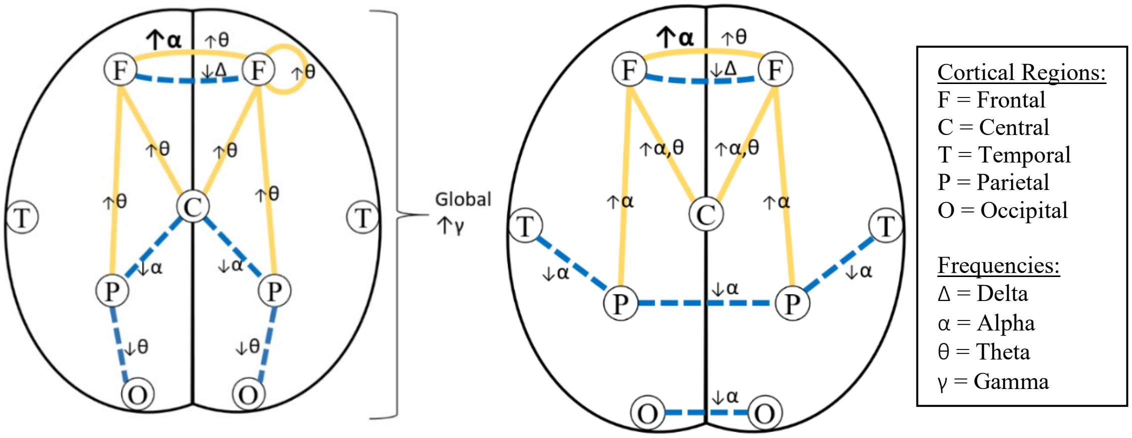


Figure 1-1 Summary of EEG regional coherence changes due to meditation.
The most reported and consistent changes across different types of meditation is interhemispheric alpha coherence in the frontal region (bolded). A) Changes in coherence as compared between expert meditators and novice non-meditators. B) Changes in non-meditators as compared to before meditation and after meditation. Yellow solid lines indicate regions of increased coherence; blue dashed lines indicate decreased coherence between regions. Each individual line indicates coherence changes that have been published in at least one meditation study, but no single study has found all of these associated coherence changes. The coherence changes may vary due to subjects, EEG devices, type of meditation, duration of meditation, coherence analysis methods, and statistical test used.

1.1.6 Performance changes due to meditation states

Like earlier studies, more recent research supports positive impacts of meditation on performance. FA meditation involves increased attentional processes on a specific object of focus, and thus may increase various aspects of performance. Evidence supports this: three weeks of training in FA (Dhammakaya Buddhist) meditation improved subjects' reaction time (Sudsuang et al., 1991). Further, reaction time and psychomotor vigilance also improved after a single FA meditation session (Kaul et al., 2010). Comparisons of meditation types indicate this benefit is strongest for FA meditation. In a study that directly compared meditation types, a single bout of FA meditation helped subjects stay on task and persist in a goal by suppressing non-task related information;

OM meditation found no such effect (Colzato et al., 2016). In the Wilkins counting test, long-term OM meditators were found to be more accurate than FA meditators when the auditory bleeps that were supposed to be counted were unexpectedly fast (Valentine & Sweet, 1999). This may be due to OM meditations having broader attention focuses than FA meditation.

Meditation has positive impacts on other measures of task performance. Depending on the type of training, it may mobilize mental resources and improve information processing. "Attentional blink" is the term given to the amount of time it takes to detect the second of two quickly presented stimuli. Meditation decreased attentional blink via increased theta phase attentional event-related potential coherence (Slagter et al., 2009).

Meditation can benefit practitioners in ways separate from task performance. A great deal of attention has been focused on its effects on emotion and drowsiness. Two studies utilized an 8-week Mindfulness-Based Stress Reduction course (MBSR) (Anderson et al., 2007; Melloni et al., 2013). The results indicated no differences in subject attention before and after their training; however, one study documented improvements in mindfulness and emotional well-being (Anderson et al., 2007). Meditation may also combat sleep deprivation and its accompanying decreased attention and increased fatigue and sleepiness (Kohler et al., 2017). One study found an increase in attentional performance for sleep-deprived, but not well-rested, participants after OM (Kohler et al., 2017), which may be an effect of increased mental resource mobilization (Kohler et al., 2017). Indeed, OM meditations are associated with occipital gamma power and decreased delta power (Cahn et al., 2010). This bilateral, frontal lobe decrease in delta power may reflect OM decreasing the homeostatic pressure of sleep or opposing it some different way (Kohler et al., 2017).

3. Traits due to meditation

Trait effects are more permanent changes in response to extensive meditation practice and repetition of the same attentional processes (Cahn & Polich, 2013). These traits are identified as differences in performance or as functional and anatomical changes due to long-term meditation practice (Hölzel et al., 2011; Lutz et al., 2009). Measuring trait effects require subjects to not meditate before testing, thus ensuring all differences in performance are not due to state effects of meditation.

Research suggests that meditative practices may increase performance in comparison to non-meditative practices. One study on performance indicated that experienced Buddhist OM practitioners had less Stroop interference, a measure that indicates better cognitive control, control of automatic responses, and/or higher executive control (Moore & Malinowski, 2009; Teper & Inzlicht, 2012). Experienced meditators also performed better on the d2-concentration and endurance test, indicating better speed, accuracy, and attentional and inhibitory control (Moore & Malinowski, 2009). Further, there is evidence that they react to changes more quickly and are more flexible in redirecting attention to new information (Hodgins & Adair, 2010). The duration of practice seems important; it has been correlated with the amount of attention, mindfulness, and awareness the meditator has, as more experienced practitioners have more extreme trait changes (Hauswald et al., 2015).

Expert meditators better task performance may be due to the functional and anatomical changes associated with long-term meditation (Hölzel et al., 2011; Lutz et al., 2009). One physiological trait positively correlated with meditation practice is increased EEG gamma power. Studies found that increased EEG gamma power in the parietal-occipital area in experienced meditators takes place during meditation as well as during rest (Braboszcz et al., 2017; Ferrarelli et al., 2013). FA, OM, and combined FA/OM meditations have higher mean gamma power both during meditation and an instructed mind-wandering task (Braboszcz et al., 2017). Since this happens during meditation and persists afterward, this gamma power increase is most likely a trait change. There are some reports of anatomical changes correlated with long-term meditation practice. Expert meditators, as compared to age-matched non-meditators, have thicker prefrontal, frontal, and temporal cortices and less age-related thinning of the cortices (Kang et al., 2012; Lazar et al., 2005). The regions identified in these studies are associated with attention, interoception, and sensory processing, which are all trained during meditation practice (Davidson et al., 2003; Kang et al., 2012; Lazar et al., 2005; Pagnoni & Cekic, 2007). Meditation also improved the functional connections of the cortex as seen in higher coherence, especially in the prefrontal and frontal regions (Aftanas & Golocheikine, 2001; Cahn & Polich, 2013).

4. Unknowns of meditation and performance

Meditation improves attention and emotional wellbeing but has limitations on its enhancements and its dedicated “fan” base may exaggerate the benefits and positive results. The effects of meditation do not improve all performance measures ubiquitously. For example, meditation did not improve cardiac interoception (the conscious perception and counting of heart rate) task performance, although brain regions associated with interoception had increased power during meditation (Khalsa et al., 2008; Melloni et al., 2013; Nielsen & Kaszniak, 2006). The attentional regions may be more active, but there were no improvements in the specific cardiac interoception since this task was not trained during meditation. Another example of this is that meditators and controls showed no differences in the Go/No-Go, which measures the ability to interpret a stimulus quickly and correctly and inhibit a trained response (Kohler et al., 2017). These subjects practiced focused attention Nidra yoga meditation, which have no focus on inhibiting conditioned responses to a stimulus that is measured with the Go/No-Go task (Simmonds et al., 2008). Training of attentional regions does not improve all potential tasks that use that specific region.

Meditation does improve specific attentional tasks. A prior study by our lab showed improvements in reaction time after meditation (Kaul et al., 2010). In this study, 10 novice meditators completed reaction time tasks before and after multiple conditions, one of which was meditation. After completing a 40-minute focused-breathing meditation, 9 of the 10 subjects had a faster reaction time. These novice meditators showed an average of 16.5 msec improvement on the psychomotor vigilance test (PVT) (Kaul et al., 2010). Our previous work showed that 40 minutes of meditation is effective in improving performance, namely reaction time improvements, but this duration of meditation was said to be long by some individual subjects (Kaul et al., 2010). To follow up on the Kaul and colleagues' study, this dissertation will investigate the impact of shorter bouts (5 and 20 mins) of meditation in novices.

The PVT is a simple and portable reaction time test that is not impacted by learning or taking it multiple times (Wilkinson & Houghton, 1982). The PVT has a simple visual stimulus and subjects must hit a button in response to the stimulus. Stimuli are presented at a random interval of 2 to 10 seconds. Since this original publication, the PVT has been widely used in performance and sleep deprivation research. PVT data contain information beyond changes in reaction time (RT). Since RTs are collected many times during the 10-minute test, PVT also measures continual vigilance and time-on-task. According to Dinges, PVT is a simple "way to track changes in behavioral alertness" with no learning or aptitude effect (Basner & Dinges, 2011). One such measure beyond RT are instances when the subject is not being vigilant and does not react to the stimulus; these lapses are defined as RT > 500ms. Kaul and colleagues did not report the changes to other PVT measures and we will be following up on that (Kaul et al., 2010)

For this dissertation, I aimed to understand the state effect of meditation in novice meditators without trait effects. I tested the hypothesis that novice meditators experience a performance benefit from a single session of meditation. Most meditation practices start with simple focused attention because it requires the least amount of training and practice. Open monitoring (OM) meditations were not chosen since they are more difficult for beginners and lacks an explicit attentional focus (Manna et al., 2010). OM meditation usually requires structure and long-term practice. For this reason, breathing-focused attention meditation was chosen. This practice can be quickly taught to non-meditators and has been shown previously to have an impact on immediate attentional performance (Kaul et al., 2010).

We are also focusing on novices to focus on the state effects of meditation. There may be certain traits that predispose someone to successful meditation and getting greater benefits from meditation (Pace et al., 2009). There are also many different covariables that may vary drastically between long-term meditators and non-meditators, such as diet, activity level, amount of motivation, and the ability to master a task. It is impossible to determine if this is directly due to the meditation training, or to other differences between groups. To address this problem, we studied novice meditators, who had little to no self-reported meditation experience.

This dissertation is unique because we investigated the effects of meditation on phase coherence, in contrast to most studies that investigate power. Our coherence measures were calculated using mean phase coherence (MPC) (Mormann et al., 2000). This algorithm calculates the instantaneous phase difference from two electrodes with signals coming from the same source brain (see Chapter 2 - Methods for computational details). MPC calculates the instantaneous phase differences of every data point, thus preserving sources of variation (Mormann et al., 2000). The MPC is independent of EEG amplitude and power and is not impacted by phase delay due to distance, and thus gives more rigorous coherence information and indicating the specific electrodes for which phase is synchronized (Schevon et al., 2007).

Chapter 2 aims to study:

1) Does 20 minutes of focused-breathing meditation improve reaction time in novices?
2) How does meditation impact other measures from the PVT?
3) Are there characteristic neurophysiological changes induced by this meditation in novices?
4) Do the neurophysiological changes correlate with changes in performance?

Finally, gathering data in the 2010 study (Kaul et al., 2010) and in Chapter 2 requires a large amount of time and research resources. Also 20 minutes may even be burdensome on some people who have very short time. In the literature it is unclear the impact of brief meditation on performance. To study this Chapter 3 aims to study:

1) Does 5 minutes of focused-breathing meditation improve reaction time in novices?
2) Can a meditation activity be successfully integrated into a freshman introductory classroom?

CHAPTER 2. REACTION TIME PERFORMANCE IMPROVES WITH 20-MINUTES OF MEDITATION IN NOVICES: ASSOCIATION WITH POWER AND COHERENCE IN THE EEG

5. Introduction

Meditation describes a wide variety of traditions that all involve the conscious control of attention (C. Kaur & P. Singh, 2015). The type of attention, training, and intent of meditation differs based on the meditation tradition and where it came from. When undergoing training, most meditation practitioners start with simple focused attention meditation, where their focus is on one object or word, such as the breath, flame, or word. Focused attention (FA) meditations often take place at the beginning and end of other types of meditation (mindfulness/open monitoring or loving kindness).

Throughout the varied histories of meditation traditions there have been fantastic claims and benefits that their training can bring, along with more modest claims, such as increased emotional regulation, stress reduction, and increased lifespan (Lee et al., 2018). experienced meditators have improved attentional blink (Slagter et al., 2009), redirection of attention to new information (Hodgins & Adair, 2010), Stroop task performance (Moore & Malinowski, 2009; Teper & Inzlicht, 2012), cognitive flexibility (Colzato et al., 2016), mental resource mobilization (Kohler et al., 2017), and sustained attention (Valentine & Sweet, 1999). Performance benefits may depend on the type of meditation and be evident only after years of training and discipline. However, it is not known whether a single session of meditation affects performance. This study aims to determine the short-term impact of meditation on physiological attention. To do this, we need to study novice meditators who do not have meditation-induced changes. Previous studies of meditation showed that novices trained in Dhammakaya Buddhist FA meditation for 3 weeks in had improved reaction times (Sudsuang et al., 1991). Conversely, mindfulness-based stress reduction (MBSR) training for 8 weeks did not change attention measures (Anderson et al., 2007; Melloni et al., 2013), supporting that performance benefits may vary by type of meditation training.

A previous study in our lab investigated meditation in both expert meditators and novices. Novices, who had no meditation experience, were tested under four 40-minute treatments (meditation, nap, a control of sitting quietly, and meditation after a night of sleep deprivation) and then given a psychomotor vigilance test (PVT). A PVT was taken before and after a 40-minute condition to measure the change in performance. There were 2 control conditions-- sedentary activity and after a nap. Subjects in the control groups performed worse on the PVT after the 40-min treatment. Laying down for a nap likely lead most subjects to fall asleep, leading to "sleep inertia", or the feeling or grogginess and reduced reaction time after waking, as has been documented in many studies (Tassi et al., 2006). The control group experienced a much smaller decline in reaction time, perhaps due to an increased afternoon dip or other cause of slightly increased fatigue. The meditation condition was a 40-minutes eye-closed focused-breathing meditation and resulted in improved reaction time, with an average of 16.65 msec faster mean PVT (Kaul et al., 2010). This performance boost was even larger (average of 27.3 msec) when subjects underwent a full night of sleep deprivation before completing the protocol (largely to due to the greater possible improvement from the slower reactions times after sleep deprivation).

While the performance boost from meditation was robust and consistent, the study had several limitations and left many questions unanswered that we aim to better understand with this study. First, in this study we are using electroencephalography

(EEG) to understand the neural dynamics during meditation that take place in novices. This study aims to determine which, if any, neural correlates that take place during meditation correspond to those that may underlie performance changes. There are many variables associated with EEG measures that may be worth examining. For example, the very first publication on EEG in 1929, by Hans Berger, described the reduction in alpha waves when the eyes were opened, known as the Berger effect or alpha blocking (Barry et al., 2007; Kirschfeld, 2005; İnce et al., 2020), which is relevant to changes seen in meditation, especially on initial eye closure. We will investigate if this eyes-closed alpha is also associated with performance changes (Barry et al., 2007). In the meditation literature, many studies have been done to understand neural dynamics of meditation and how they differ between meditation subtypes. In most of this literature, EEG dynamics have been predominately analyzed by looking at power, coherence, and complexity. The 'power' of each frequency band, delta, theta, alpha, beta, gamma, of the raw EEG can be quantified using a Fast Fourier Transform (FFT) converting the original signal into its frequency components. Power changes, whether relative or absolute, vary highly based on analysis method and type of meditation. It is argued that different types of power changes indicate different types of meditation induced neural changes such as focused attention, open monitoring, and self-transcending (Travis & Shear, 2010).

Coherence, in general, is a measure of functional connectivity and synchronization between different brain regions. The meditation literature has calculated this value in a multitude of ways including the measure of synchronization or correlation using power spectral density (Dissanayaka et al., 2015) which assume that temporally concurrent changes in power indicate changes in coherence. A majority of meditation research that has analyzed coherence has compared power using FFT, and then calculated the coherence spectra. The specific methodological details are often lacking in these studies, but the most robust findings showed that long-term meditators generally have increased coherence during meditation or in comparison to non-meditator controls. Specifically, transcendental meditation (TM) practitioners have been extensively reported to have increased alpha coherence (Levine, 1976; Orme-Johnson & Haynes, 1981; Travis, 2001; Travis & Wallace, 1999) and perhaps theta coherence during meditation (Tomljenović et al., 2016). Those who practice Sahaja Yoga show increased theta coherence, especially in the left frontal cortex (Aftanas & Golosheikin, 2003; Baijal & Srinivasan, 2010). These findings are not necessarily unique to experts, as some novice TM practitioners showed a similar increase in alpha coherence (Dillbeck & Bronson, 1981; Gaylord et al., 1989; Levine, 1976). However, in a more recent study, this alpha coherence was found to be absent in novices (Aftanas & Golocheikine, 2001), but in another study increased after just 2 months of TM meditation training (Travis & Arenander, 2006). Although these findings appear generally valid, they do not specifically address phase or other aspects of the EEG signals in their calculations.

To take a more rigorous analytical approach to coherence and power, we applied phase synchronization to analyze functional connectivity during meditation. Other phase locking methods have found increased gamma (25-40 Hz) coherence during rest and during loving kindness meditation (Lutz et al., 2004), increased theta coherence during OM Vipassana meditation (Slagter et al., 2009), and increased alpha coherence during TM (Travis et al., 2010). Our coherence measures were calculated using mean phase coherence (MPC) (Mormann et al., 2000). This algorithm works by calculating the instantaneous phase difference from two electrodes assuming that the signals come from the same source, the brain (see Methods for more details). This is also unique to the meditation field since it will provide phase information independent of amplitude/power, which has yet to be applied to meditation EEG. This phase locking also removes the phase delay due to distance (Schevon et al., 2007), allowing more accurate comparisons between disparate electrodes which could help determine if meditation increases synchronization across the brain.

To understand the impact of a single session of mediation, in this study we will apply MPC to investigate the neural dynamics during meditation in novice meditators. In a study of similar voluntary abdominal breathing (VAB), EEG showed distinct changes over time (Fumoto et al., 2004). This abdominal breathing, which lasted for 20 minutes with eyes closed, showed the expected Berger alpha waves at the beginning of the activity, with a consistent peak at 10 Hz in most subjects. After splitting alpha into high (10-13 Hz) and low (8-10 Hz) frequency activity, low frequency alpha showed a steady decrease in power throughout the VAB and disappeared after 6-7 minutes. Later, a lower amplitude wave of the high alpha steadily increased in power starting at 5 minutes until the end of the study (Fumoto et al., 2004). The authors attributed this later 10-13 Hz high frequency alpha to feelings of vigor and reduced anxiety. Unlike other papers which state that meditation-induced EEG patterns do not change throughout practice in expert meditators (Travis & Wallace, 1999), novices during breathing focused meditation can show distinct changes in EEG power and may also show changes in coherence over time. This will also be investigated here.

We also determined whether short meditation improved e reaction time in novice meditators. , For many novices, the 40-minutes of meditation used in our previous experiment was a long time to focus on their breath, which may increase confounding effects when the mind wanders, and is longer than most individuals will be able to sustain if they wish to adopt a daily practice of meditation. The present study shortened meditation duration to 20 minutes and examined the effects on PVT sustained attention performance.

By gathering EEG data during meditation, we wanted to investigate the EEG dynamics during focused breathing meditation. We hypothesized that alpha and theta power would be highest in frontal electrodes, due to the concentration and attention regulation needed during meditation (Cahn & Polich, 2013; Lee et al., 2018). We also hypothesize that this alpha and theta power will change over time, with a drop in power over time as novice subjects are unable to maintain concentration (INANAGA, 1998). Not only are we expecting to see high power, but meditation is also hypothesized to increase frontal coherence, which has been supported in multiple different prior studies (Aftanas & Golocheikine, 2001); Aftanas & Golocheikine, 2002; Arambula et al., 2001; Ghista et al., 1976; Huang & Lo, 2009; Khare & Nigam, 2000; Travis, 2011). When these EEG measures are related back to performance, we hypothesize that those subjects with the best coherence between frontal electrodes will have the largest improvements in PVT performance. Given the high amount of alpha with eyes-closed, especially in occipital cortex and more posterior regions, we investigate whether there may be higher alpha coherence between occipital electrodes and parietal electrodes. We further hypothesize that occipital alpha power will correlate with reaction time measures. Given the exploratory nature of these studies, we also assess a number of other EEG variables that may be associated with meditation.

6. Methodology

2.1.1 Subjects

Non-meditators with were recruited for this project, including no experience (>6 months) with meditation, mindfulness, or yoga. All subjects (n=25) were 18 to 55 years old, right-handed, and appeared to be in excellent health and did not admit to medical or psychiatric illness or sleep disorders. Subjects were instructed to abstain from nicotine, alcohol, and other drugs on the study day. They were also instructed to keep a regular sleep-wake schedule prior to testing day. Subjects were recruited by campus advertisements at the University of Kentucky or word of mouth. All procedures were approved by the University of Kentucky Institutional Review Board and informed consent was obtained from all subjects. \

2.1.2 Procedure

On the test day, novice meditators took a 10-minute PVT on the computer (PC-PVT, (Khitrov et al., 2014) using a gaming mouse for better accuracy. The PVT randomly presented subjects with a stimulus every 2 to 10 msec for the duration of the 10 minutes. Given the very simple nature of this test, no learning or improvement has generally been observed after repeated trials (Basner & Dinges, 2011). However, to eliminate even slight “first-time” effects, each subject was given a practice trial on the PVT prior to the start time. After completing the 10-minute PVT, subjects were taught how to meditate. Focused breathing meditation was chosen since it is easily learned by beginners and is often used in the beginning or end of other types of meditation training.

All subjects were trained by the same instructor using the following script to ensure uniformity.

> "We will now begin the focused breathing meditation. Sit straight in your chair with your feet flat on the ground with your shoulders aligned with your hips. Place your hands in your lap or in a comfortable position. During this meditation, focus only on your breathing. When your thoughts wander, keep bringing it back to your breath. Close your eyes and I will tell you when 20 minutes is over. Do you have any questions?"

Post-meditation, the subject completed a final 10-minute PVT.

For a subset of these subjects (n=13), EEG was applied before the meditation intervention to gather information about cortical activity. For 7 subjects, an EMOTIV Epoc+ System was used to record meditation-induced brain activity. This dry electrode system gathered data at AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4 with reference at the mastoid. To confirm that the EMOTIV was accurately gathering data, 5 subjects underwent EEG recording with a more sophisticated gold cup electrode in the OpenBCI Electrode Cap with Cyton Biosensing Board (OpenBCI). Electrodes were applied to the following locations to match the EMOTIV montage: F3, F4, F7, F8, Fp1, Fp2, P7, P8, T7, T8, O1, and O2, with reference to the ear. All EEG was sampled at 128 Hz

Data was combined from both recording devices as both have been shown to be highly accurate and comparable to the field standard gold-cup electrodes (LaRocco et al., 2020), and produced similar quality recordings in our study. The EMOTIV Epoc+ has been shown to be 70-94% accurate and the OpenBCI systems have been shown to be 79-96% accurate (LaRocco et al., 2020). To make coherence comparisons between the two devices, power analyses are between locations that were recorded by both devices: AF3, F7, F3, T7, P7, O1, O2, P8, T8, F4, F8, and AF4 (Supplementary Figure 1).

7. Data Analysis

2.1.3 PVT

PVT data was postprocessed using REACT (Ambulatory Monitoring, Inc.) and analyzed with PC-PVT Tester (Khitrov et al., 2014). Reaction time (RT) was determined for each stimulus from the presented stimulus until the output (the subject hit the button). Two types of errors were recorded: lapses (RT >500 msec) and false starts (subject giving an output without a stimulus). Mean RT, speed (mean 1/RT), number of lapses, number of false starts, number of total errors (number of lapses + false starts), slowest 10% RT, 1/slowest 10% RT, fastest 10% RT, and 1/fastest 10% RT were analyzed.

2.1.4 EEG

EEG data during the 20-minute meditation was processed using MATLAB R2021a. Data was band pass filtered from 0.1 to 60 Hz using a 4th order Butterworth filter. The Butterworth was chosen since it is designed to be maximally flat as compared to other filters that introduce ripples into continuous data (Laghari et al., 2014). One subject was removed due to poor EEG signal quality. Artifacts in the rest of the subjects were identified first by manual inspection, by which some slower frequency and high amplitude distortions were seen which we attributed to headset movement. Automatic detection of these artifacts was done by taking the standard deviation of raw signals to flag epochs above the 95th percentile and remove 1 second epochs that had unusually high deviation as compared to the average raw signal. Manual inspection of flagged artifacts shows that all slow frequency, high amplitude artifacts were correctly flagged, and data were removed.

Continuous data were split into the following frequencies: delta (0.5-3 Hz), theta (3-7 Hz), alpha (7-13 Hz), beta (13-30 Hz), and gamma (30-45 Hz). We then calculated mean phase coherence, as first applied to EEG by Mormann and colleagues in epilepsy patients (Mormann et al., 2000). This method allows for calculating instantaneous phase differences for each selected electrode pair at each time point recorded. First the Hilbert transform was used to determine the phase of two signals, ϕ. Then MPC is determined using the following:

$$\text{MPC} = \frac{1}{T}\sum_{t=1}^{T} e^{i(\phi_t^n - \phi_t^m)}$$

T is the total number of time points. $\phi_t^n - \phi_t^m$ is the instantaneous phase difference between the m^{th} and n^{th} electrodes at time point *t*. The symbol *i* denotes an imaginary unit. First the difference of the instantaneous phases is determined and transformed to get discrete phase coherence values placed on a unit circle. After all points are plotted on the unit circle, the mean of all samples is taken to determine MPC (Schevon et al., 2007; Yoshida et al., 2020).

The output of these calculations is a complex number made of both real and imaginary components, which contain power (μV) and phase angle data (unitless), respectively. These power and coherence data were then binned into 30-sec epochs with 15-sec overlap (epochs are sequentially numbered from 1-78). Interhemispheric synchronization was calculated for all electrode pairs of the same location on either hemisphere: AF3/Fp1-AF4/Fp2, F3-F4, F7-F8, T7-T8, P7-P8, and O1-O2. Intrahemispheric coherence was calculated for all electrode pairs. There is no consensus on how to partition regions of electrodes, so regional coherence was calculated by averaging together electrodes of similar locations: frontal (AF3/Fp1, AF4/Fp2, F3, F4, F7, F8), parietal (P7, P8), temporal (T7, T8), and occipital (O1, O2). Any MPC value above 0.3 is considered to show more coherence than random noise (this was calculated from random mixing of EEG time points, and then calculating the MPC from randomized data).

Statistical analysis was completed using JMP Pro 15. PVT data was analyzed using paired t-tests to determine if subjects had different performance before and after meditation. Relationships between EEG measures and PVT data were investigated using Pearson's correlation and scatter plots with linear and quadratic models with non-parametric smoothing. Due to the large number of comparisons, we implemented a multiple comparison correction and α was set as 0.01. Time points that did not meet this adjusted threshold were considered to still be associated with PVT data, when ten or more time points had $p<0.05$, as a Bernoulli process shows this to have a 0.05% chance of being due to random chance.

8. Results/Data Analysis

2.1.5 20 Minutes of Meditation Improves PVT Performance

Given our prior findings with 40 minutes of meditation (Kaul et al 2010), We tested the hypothesis that 20 minutes of meditation would improve reaction time from pre-meditation to post-mediation in novice meditators. Meditation significantly improved mean reaction time ((t(24) = 2.138, p=0.02), paired t-test). This averaged to a performance boost of 8.9 milliseconds on mean RT (Figure 2.1). Before meditation subjects had an average reaction time of 266 msec (+/- 30) and after meditation was 257 msec (+/- 27).

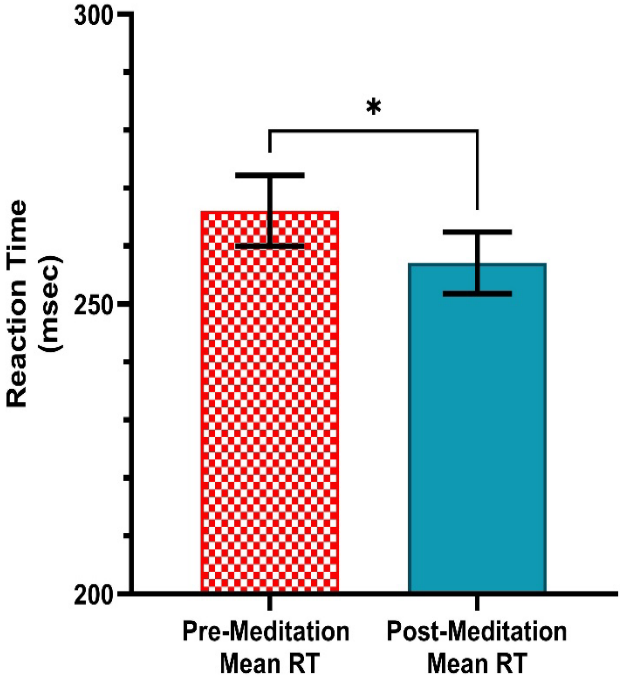


Figure 2-1: 20 Minutes of meditation improves PVT reaction time.

Subjects (n=25) did the PC-PVT before and after 20 minutes of mediation. that did the meditation, performance on the PVT improved, on average 8.9 msec from pre-meditation to post-meditation. Error bars denote SEM. *p=0.02 using paired t-test.

To understand how our subjects were improving, we analyzed other PVT variables. During the 10-minute PVT, subjects may have absences in vigilance when reaction times are longer than 500 msec, called lapses. Our subjects showed a significant reduction in lapses ((t(24) = 2.139, p=0.02), paired t-test) from an average of 1 lapse to an average of 0.5 lapses after meditation. An individual subject cannot have a partial lapse, as lapses are a discrete variable that is counted. Many of the subjects had 0 lapses and drove the average to 0.5. When the slowest and fastest reaction times were analyzed, the 10% slowest reactions times failed to reach significance (p=0.07), but there was a trend that post-meditation improved the slowest reaction times (pre-meditation: 398 msec, and post-meditation: 376 msec). There was no change in the fastest reaction times before and after meditation.

During the 10-minute PVT, reaction time is sampled about 94 times. The inverse of individual reaction times was graphed to look at the change in performance over time. This change in performance was determined with a linear fit and the slope was taken to determine the change in RT over the full 10-minute test. These slopes were then compared before and after meditation. Before meditation, subjects had slower reaction times as the trial continued (m=-0.034). We found that meditation reduces this change overtime (m=-0.016) ((t(24) = 2.146, p=0.02), paired t-test).

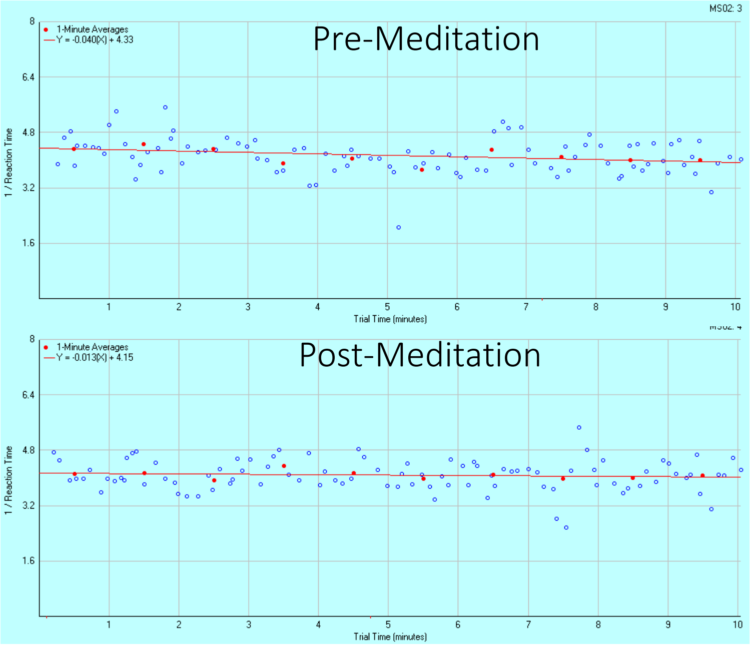


Figure 2-2 Meditation improves vigilance over the 10-minute PVT.
One subject's representative graphs showing a decline in performance before meditation (m=-0.40) and a lesser decline after meditation (m=-0.013). Blue open circles indicate individual reaction times (RTs), red closed dots indicate minute averages in RT, red line is the linear fit of all RTs.

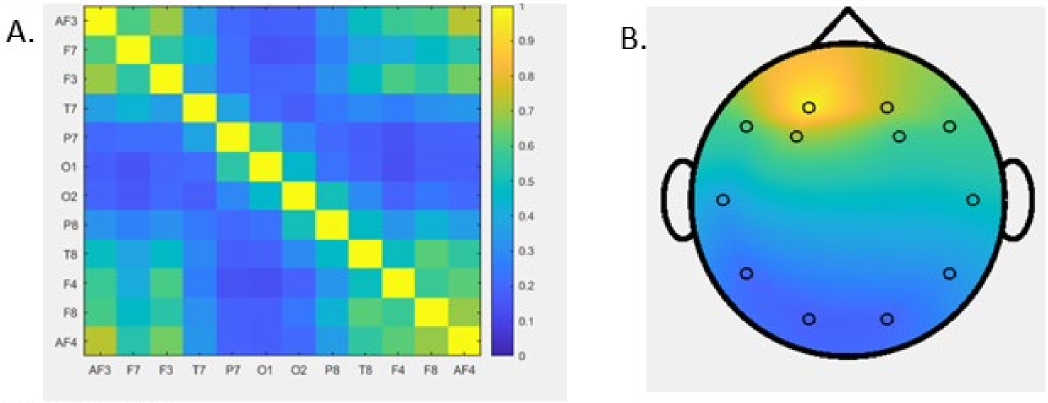
2.1.6 MPC showed high frontal alpha and theta coherence

MPC (mean phase coherence) was used to calculate coherence for all possible electrode pairs and in individual frequency bands. Values vary from 0 to 1, with 0 indicating no coherence and 1 indicating perfect coherence. We defined coherence above 0.5 as moderate coherence and over 0.75 as high coherence.

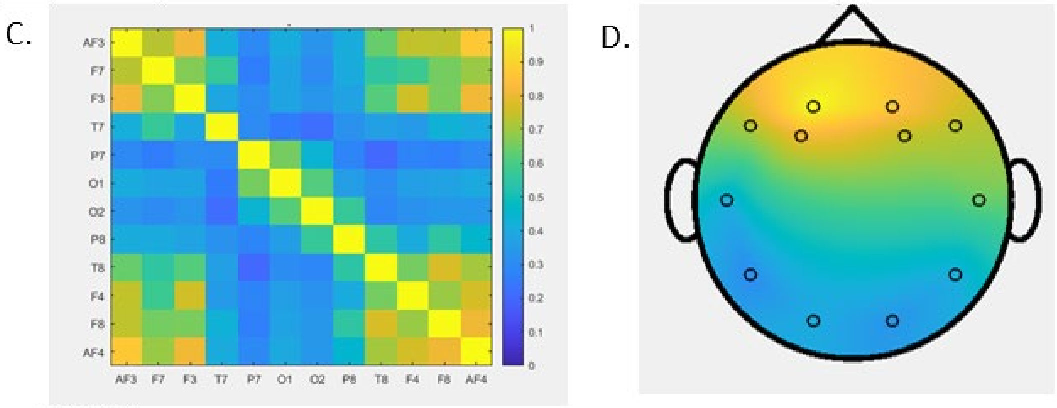
Frontal electrodes show strong intrahemispheric and interhemispheric coherence. This was strongest in the alpha band, but also was visible in the theta band (Figure 2.3). Prefrontal alpha electrodes (AF3/Fp1 and AF4/Fp2) show high coherence with (AF3-AF4, AF4-F3, AF4-F4, AF3-F3, AF3-F4, F3-F4). Frontal-temporal coherence was also high in the alpha band and moderate in the theta band. Occipital electrodes showed moderate interhemispheric coherence and occipital-parietal alpha coherence. This pattern is detailed in Figure 2.1

Parietal and temporal electrodes show hemispheric differences in MPC (Figure 2.4). Investigations into parietal electrode pairs show differences in coherence between right and left side, with right parietal-temporal (P8, T8) showing higher alpha coherence with distal electrodes. P8 (alpha MPC=0.41) and T8 (alpha MPC=0.42) showed more widespread coherence with occipital, temporal, and frontal electrodes. Left hemisphere P7 (alpha MPC=0.32) and T7 (alpha MPC= 0.33) only showed coherence with occipital and temporal electrodes, with no frontal coherence.

Beta (13-30 Hz)



Alpha (7-13 Hz)



Theta (3-7 Hz)

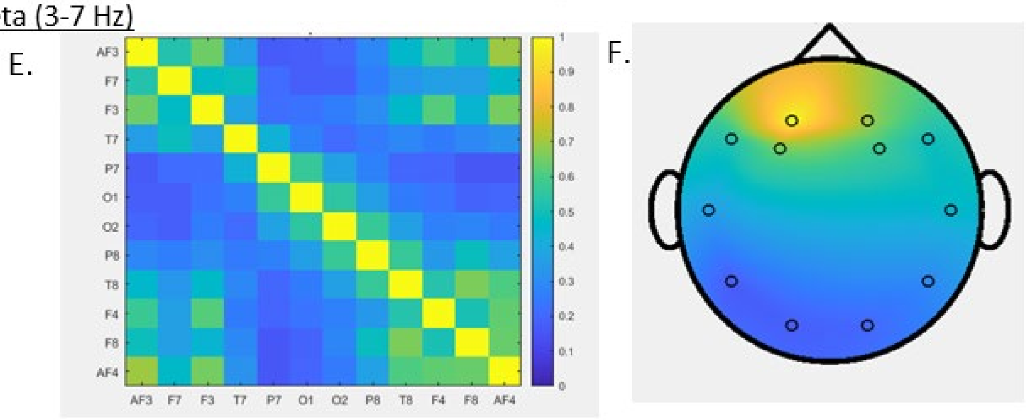


Figure 2-3 Novices have high frontal alpha and theta coherence during meditation. A) Beta MPC for all electrode pairings. B) Beta MPC for electrode AF3. C)Alpha MPC for all electrode pairings. D) Alpha MPC for electrode AF3. E) Theta MPC for all electrode pairings. F) Theta MPC for electrode AF3. Color scale indicates MPC with yellow for perfect coherence and blue indicating no coherence. All images indicate a single representative epoch. Any MPC larger than 0.3 has more coherence than random noise.

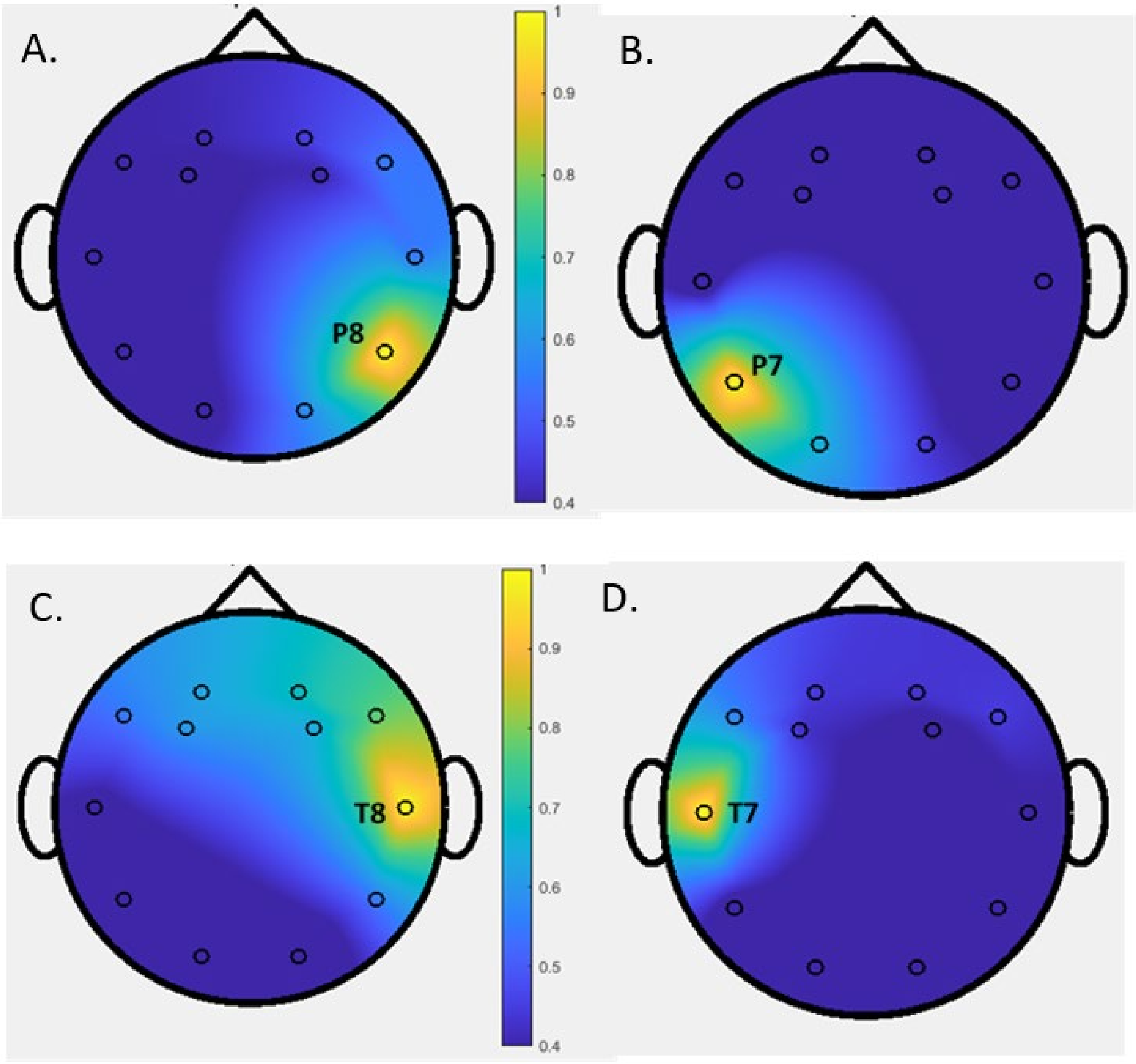


Figure 2-4 Novices show higher right-side alpha coherence in the temporal and parietal electrodes.
A) P8 shows higher MPC for further away electrodes (frontal and prefrontal) than B) P7. C) T8 shas higher and more distal MPC than D) T7. Color scale indicates MPC with yellow for perfect coherence and blue indicating low coherence. Any MPC larger than 0.3 has more coherence than random noise.

2.1.7 EEG Power Correlates with Reaction Time

For the subjects with usable EEG (n=12), there was a non-significant trend in reaction time improvement after meditation (p = 0.079), with an average of 10.6 sec (+/-23) faster reaction time. Of these subjects, 7 showed improvement in mean RT after meditation and 5 either had no change or had slower mean RT after meditation. With this distribution of some subjects improving, some showing no differences, and some having worse reaction time after meditation we investigated the associations between EEG power and coherence to the PVT measures.

EEG power was correlated with difference in PVT mean reaction time (RT) (Figure 2.5). Prefrontal (AF3, AF4) gamma power (Supp. Figure 2) showed a correlation in the first three minutes of meditation (AF3: $p<0.01$ for epoch 6, $p<0.05$ for 2-5, 7, 10-12, and 55; AF4: $p<0.01$ for epochs 5 and 6, $p<0.05$ for 1- 4, 7, 10, 11, and 50), where subjects with lower gamma power show larger performance boost. No other electrodes had significant gamma power correlations. Alpha power correlated with RT in frontal electrodes F3 ($p<0.05$ for 6, 7, 10, 12, 20, 26, 27, 29-31, and 68) and F4 ($p<0.05$ for 6, 7, 10, 12, 20, 26, 27, 29-31, and 68) (Supp. Figure 3). F3 and F7 beta power also correlated with difference in RT (F3: $p<0.01$ for 58, 59, and 60, $p<0.05$ for 7-20, 29-31, 35, 41, 42, 45, 48-53, 57, 61, 64, 65, 67-69, 72, and 73; F7: $p<0.01$ for 51 and 58, $p<0.05$ for 34, 35, 49, 50, 52-54, 57, 59, 62, and 63) (Supp. Figure 4). F3 alpha power correlated during the first ten minutes of recording. Frontal alpha and beta power notably did not correlate with PVT in the first minute of mediation. F7 beta power correlated during the 8 to 16 minutes. F4 alpha power correlated with performance but showed no specific temporal pattern. Occipital alpha power also showed an association with difference in RT (O1: $p<0.05$ for 2, 4-7, 9-17, 19, 29-31, 35, 43, 44, 47, 48, 50, and 51) (Supp. Figure 5). Frontal delta and theta power showed no correlation. Parietal and temporal electrodes of any frequency band showed no association.

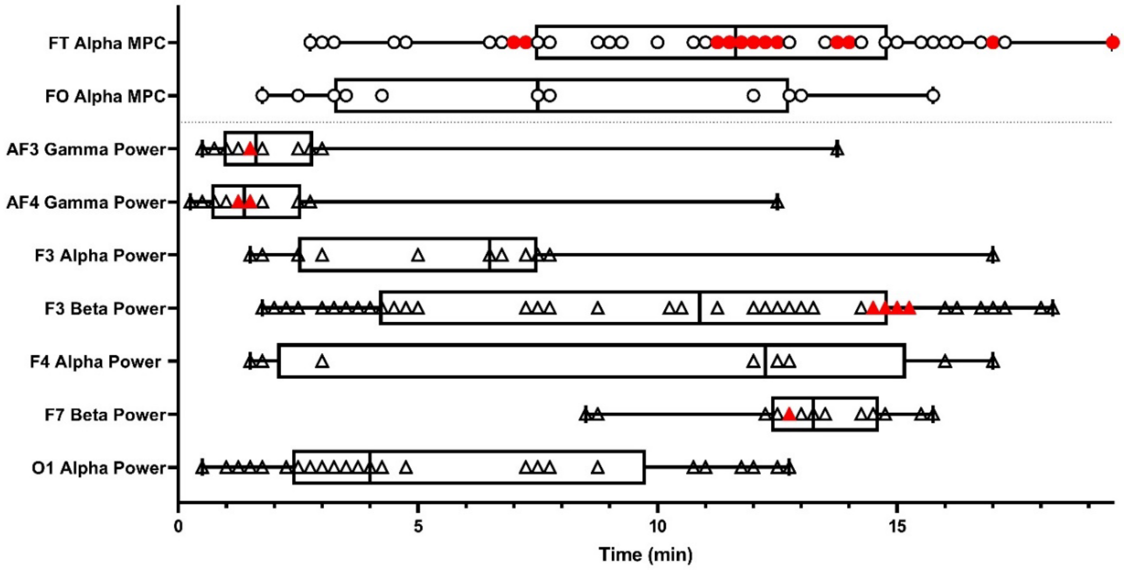


Figure 2-5 Temporal differences of EEG power and MPC correlates with PVT reaction time (RT) during meditation.
Throughout the 20-minutes of meditation, all EEG epochs that showed a strong correlation with the difference in PVT RT had a vastly different distribution based on electrode, frequency bin, and power/MPC. Prefrontal (AF3, AF4) gamma power showed a correlation in the first three minutes of meditation. Frontal alpha and beta power notably did not correlate with PVT in the first minute of mediation. Frontal-temporal MPC had the most epochs correlated with RT. Boxes indicate the median and 25th and 75th quartiles, and whiskers indicate the first and last significant epoch. Red solid points $p<0.01$ Pearson's correlation to difference in mean RT, black hollow points = $p<0.05$. Circles indicate epochs of significant MPC correlation, triangles indicate significant power correlations.

2.1.8 EEG Alpha Coherence Associates with Reaction Time

EEG mean phase coherence (MPC) in the alpha band was associated with difference with PVT reaction time (Figure 2.5). First, we looked at MPC for interhemispheric coherence, showing the synchronization across both hemispheres. None of the electrode pairings passed our adjusted alpha value or 10 epoch threshold for significance. F7F8 MPC did show eight epochs of correlation with RT with $p<0.05$, which is worth noting. No other frequency bands or electrodes were correlated. Then synchronization between cortical regions were correlated to PVT RT. Frontal-temporal alpha MPC show significant correlations for the most time points (Supp. Figure 6). This means subjects with higher MPC between the frontal and temporal electrodes correlated with better improvements in RT. This correlation was also noted for alpha MPC frontal-occipital and temporal-occipital coherence. Coherence between other regions or in other frequency bands were not associated with difference in PVT RT.

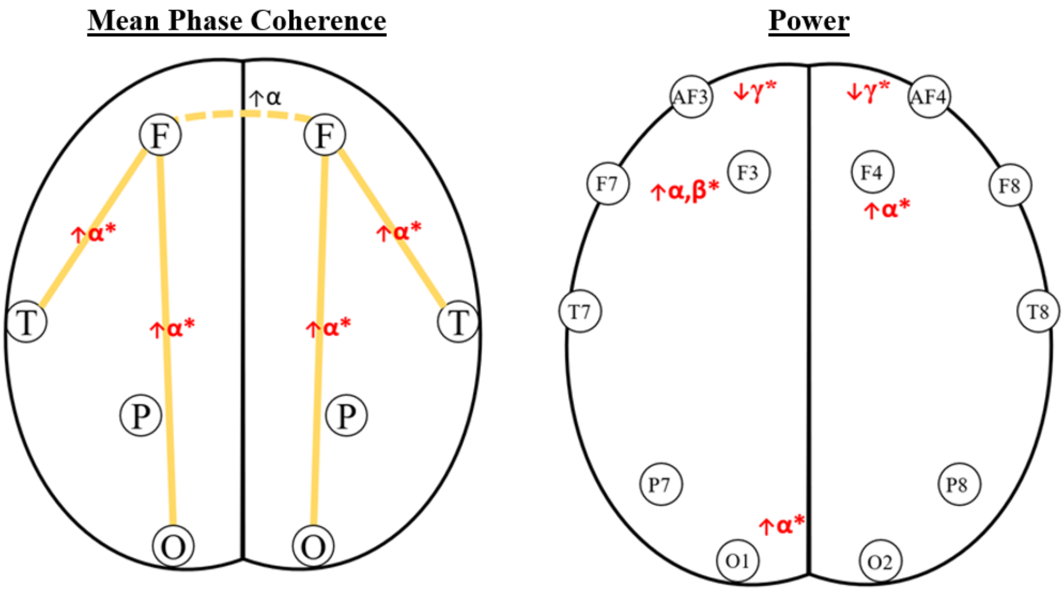


Figure 2-6 Summary of EEG findings in relation with PVT Performance.
This figure notates all data that correlated significantly with mean difference in PVT due to 20-minutes of meditation. Left: Mean Phase Coherence (MPC) in the alpha band shows increase coherence and synchronization between the frontal-temporal and frontal-occipital regions are associated with an improvement in PVT performance. Right: Power correlates with PVT performance, showing that increased alpha and beta power, and decreased gamma power lead to better PVT performance. Yellow, solid lines and red* indicate $p<0.05$ from Pearson's correlation for at least 10 epochs. Dashed line indicates $p<0.05$ for only 9 epochs, which still is a less than 2% chance of being random noise.

9. Discussion

In the current study, we showed that 20minutes of meditation improved PVT reaction time in novices. Subjects had faster mean RT, had fewer lapses, and maintained vigilance better during the 10-minute PVT after mediation compared to baseline before meditation. These findings support a previous study in our lab that a single 40-minute meditation improved PVT reaction time (Kaul et al., 2010). Our data show that 40 minutes is not needed for significant performance benefits, and a shorter 20 minutes of focused breathing can still impart benefits.

It should be noted that 40 minutes of meditation improved PVT reaction time 16.7 msec (Kaul et al., 2010), whereas our subjects had an average of 8.9 msec of improvement. This is due to large variation in the difference between pre-meditation RT and post-meditation RT. Kaul and colleagues had all ten subjects improve RT after meditation (2010). Of the twenty-five subjects in this study, only seventeen had an improvement in mean RT; eight subjects had no change or worse RT after meditation. Although the majority of subjects did have RT improvements due to the meditation, some did not benefit. This could be due to 20 minutes not being a long enough time to benefit the subject or a potential lack of motivation or other confounding variables in a subset of subjects.

Our results are consistent with previous studies that demonstrated that meditation improved attention in novices. Rather than a single session, these studies relied on longer training paradigms. Studies of FA support that the duration of training is directly correlated with reaction time improvement (Kohler et al., 2017; Sudsuang et al., 1991), but our data support that a single session is enough to see significant improvement. Specifically, three weeks of Dhammakaya Buddhist meditation training in novices improved performance on visual choice reaction time, and this performance boost was even larger after six weeks of meditation training (Sudsuang et al., 1991). Mindfulness meditations may or may not improve attentional performance, as studies show different effects of training (Anderson et al., 2007; Slagter et al., 2007; Slagter et al., 2009). An 8-week Mindfulness-based stress reduction (MBSR) course did not improve reaction time during a sustained attention test (Anderson et al., 2007). A longer three month mindfulness training in Vipassana meditation was shown to have better attentional performance by showing a smaller attentional-blink compared to the novice group (Slagter et al., 2007; Slagter et al., 2009). This task does not measure speed of reaction, but rather accuracy of identification. The authors attributed this to the experimental subjects not needing as much attentional resources to identify the first target and were more likely to detect the second target (Slagter et al., 2009).

In addition to performance measures, we explored EEG during meditation and how it may relate to the performance boost. PVT performance was correlated with multiple EEG power measures. Alpha power was the most associated with improvement of mean reaction time. Frontal alpha is associated with alertness, attention, and task load (Klimesch, 1999). Meditators have been shown to have higher frontal alpha power than non-meditators (Aftanas & Golocheikine, 2001; Aftanas & Golocheikine, 2002; Arambula et al., 2001; Ghista et al., 1976; Huang & Lo, 2009; Khare & Nigam, 2000; Travis, 2011). In our novices, there was a strong association in prefrontal and frontal electrodes, where subjects with higher alpha power during meditation had a better change in performance. Our data also showed a correlation with lower frontal gamma power and improved attentional performance. The implications of this result are unclear. Parietal-occipital gamma increase in activity is considered a meditation trait and has only been noted in advanced meditators (Braboszcz et al., 2017; Cahn et al., 2010; Ferrarelli et al., 2013). It is possible that our correlation in gamma could be related to ocular muscle activity, as the association was only seen in AF3 and AF4, and does not indicate any association with cortical function (Olson et al., 2016).

We next examined coherence within the EEG during the 20-minute meditation bouts. To improve the rigor of these EEG measures, we used mean phase coherence (MPC) analysis to measure synchronization of cortical regions. The majority of studies of EEG synchronization during meditation look at correlations of power changes (Aftanas & Golocheikine, 2001; Aftanas & Golosheikin, 2003; Dillbeck & Bronson, 1981; Gaylord et al., 1989; Murata et al., 2004; Tomljenović et al., 2016; Travis, 2011; Travis et al., 2010; Travis et al., 2017; Travis & Wallace, 1999). (See Chapter 1, Table 1.1 for a summary of coherence analysis in meditation). Using power correlations shows concurrent amplitude changes in the same frequency band, but neglects phase information. Recent hypotheses into neuronal dynamics propose that strong effective connectivity requires coherence or rhythmic synchronization between neuronal groups sending and receiving signals (Fries, 2005, 2015). Inputs that rhythmically and consistently arrive at times of high input would benefit from this enhanced connectivity, and without this coherence, inputs would arrive at random time in the phase and have less effective connectivity (Fries, 2015). Following this hypothesis, MPC more accurately describes the communication between cortical regions during meditation.

Our EEG data showed the following: high alpha coherence in prefrontal and frontal electrodes, moderate alpha coherence between occipital and parietal electrodes, and more coherence on the right side of the brain than the left. Increase alpha synchronization , specifically, showed significant correlation with better PVT performance. This was seen most strongly for the frontal-temporal regions but was also more wide-spread in the frontal-occipital and temporal-occipital MPC values. High alpha coherence is the most widely reported result in studies of meditators compared to controls, and has been perhaps the most well established change that occurs with meditation (Dillbeck & Vesely, 1986; Levine, 1976; Murata et al., 2004; Newandee & Reisman, 1996; Travis & Arenander, 2006; Travis et al., 2010; Travis et al., 2017). Alpha coherence has been suggested to be a default state for local cortical neuronal groups to synchronize, and it may help mediate attentional processes, although the evidence is limited (Fries, 2015). The individual subjects we found with better coherence may have better communication between cortical groups associated with attention, which in turn contribute to the performance benefits found in this study.

We did not find an association between meditation theta power or coherence and PVT performance. This may be due to our subjects having a lack of long-term meditation training. More experienced meditators, including those who have received only weeks of training, have been shown to have an increased frontal theta power and coherence (Baijal & Srinivasan, 2010; Cahn et al., 2010; Cahn & Polich, 2013; Gaylord et al., 1989; Tang et al., 2009; Tsai et al., 2013). These more experienced meditators have had longer time to practice and presumably become better at meditation and attentional control. Theta dynamics during meditation have remained controversial as other studies have noted reduced theta activity during meditation (Dunn et al., 1999; Huang & Lo, 2009). It is also possible that our specific type of meditation was not an engaging enough task to induce theta power changes. It has been suggested that frontal theta in particular is related with the maintenance of attention and vigilance during specifically during directed tests as compared to a more passive task (Baijal & Srinivasan, 2010;

INANAGA, 1998). Since our procedure measured EEG during meditation and not the PVT, this may account for our lack of significant theta power and coherence findings. Future studies should look at the theta band during the reaction time test to see if novices have any changes to theta power or coherence due to the single session of meditation.

Human neural dynamics change rapidly over time, and our data shows trends that change over time. Prefrontal gamma power (AF3 and AF4) was correlated with attentional performance in the first three minutes of meditation, whereas frontal alpha and beta notably lacked correlation during the first minute of meditation. Other noteworthy differences are that two correlations with performance, F7 beta power and temporal-occipital alpha MPC, did not show a relationship with RT until the second half of meditation. Few studies of EEG during meditation have looked at the changes across the meditation period, but rather select a small sample of data, usually less than one minute for coherence and other complexity analysis (Aftanas & Golocheikine, 2001; Aftanas & Golocheikine, 2002; Aftanas & Golosheikin, 2003; Dissanayaka et al., 2015; Gaylord et al., 1989; Huang & Lo, 2009; Murata et al., 2004; Tomljenović et al., 2016; Travis, 2011; Travis & Arenander, 2006; Travis et al., 2010; Travis & Parim, 2017). One such influential study of TM had meditators EEG binned for the 1st, 5th, and 10th minutes during eyes-closed rest and TM practice (Travis & Wallace, 1999). Coherence values were not significantly different, but there was a non-significant but still noteworthy increase in coherence around the middle of the meditation. This paper has been cited multiple times as the reasoning behind coherence values not changing over time and therefore limiting data used for analysis (Travis, 2011; Travis & Parim, 2017). Analysis of more specific time points have revealed interesting findings in experienced meditators.

One study of experienced Sahaj Samadhi meditators also showed that theta power was not constant and was highest in the middle of their meditation (about 8 to 12 minutes in) (Baijal & Srinivasan, 2010). Zen meditators had the highest relative beta power during the last 5 minutes of a 40-minute meditation (Huang & Lo, 2009). Investigations that only look at a subset of EEG data during meditation would have missed such associations over time.

A limitation to this study is that there was no EEG data for control or reference. One problem in the meditation field is that there is no standardized and generally accepted control. Some studies rely on an eyes-closed rest for non-meditation conditions (Aftanas & Golocheikine, 2001; Gaylord et al., 1989; Newandee & Reisman, 1996; Travis & Arenander, 2006; Travis & Parim, 2017; Travis & Wallace, 1999). However, the act of closing eyes immediately increases alpha power, markedly in the occipital lobes (Barry et al., 2007), and is arguable a first step toward a "meditative state". Our data shows that this occipital alpha power as soon as eyes were closed was correlated to attentional performance. Our data also supports that this eyes-closed alpha could be associated with the performance benefits of meditation, and other studies of meditation support that occipital cortex dynamics are characteristic of higher states of consciousness during meditation (Huang & Lo, 2009). Because of this, we do not think eyes-closed rest is a good non-meditation condition. Eyes-open rest conditions as controls (as used in (Takahashi et al., 2005) differ greatly because they are precisely missing the alpha power increases due to closing of the eyes and thus may vary too much from eyes-closed meditation. Other options need to be considered. Future investigations should compare multiple types of control conditions (both eyes closed and eyes open) and examine their EEG dynamics in comparison to meditation.

Another limitation of our study is that the exploratory design only lends itself to descriptive and correlative results. Our data shows an association between meditation EEG power and coherence and performance changes during the PVT. We cannot say that these changes in EEG during meditation are in any way causative, but the relationships between EEG and RT are noteworthy, and could be manipulated in various ways to test or at least suggest a causative role. Subjects with higher EEG alpha power and coherence had a better performance boost in the PVT. It would be interesting to see if these subjects had an easier time maintaining attention. Future studies should investigate this relationship further.

In conclusion, our data shows that 20 minutes of meditation improved PVT performance, and that these performance changes were associated with EEG measures during meditation. Given the wide range of methods used for coherence measures and other EEG variables during meditation, we suggest more consistent and rigorous measures be adopted (such as MPC used here) and that assessment of these measures be done throughout the entire meditation period.

CHAPTER 3. THE EFFECTIVENESS OF SHORT MEDITATION ON ATTENTIONAL PERFORMANCE: A QUICK CLASSROOM ACTIVITY

10. Abstract

Undergraduate students suffer from stress and attention problems throughout their academic career. This is a great time for students to learn a new skill; meditation practices have been shown to improve mental and physical health and our activity can introduce them to this beneficial practice. Utilizing the learning-cycle approach, we had students first engage with a problem, explore interpretations, conduct a meditation experiment, and then interpret and explain results. This short activity investigates the impact of focused-breathing meditation on the attention of students using the psychomotor vigilance test (PVT). The within subjects' design showed that a majority of students see reaction time improvements with just 5-minutes of meditation or 5-minutes of being sedentary. This has been repeated over many years and in both an introductory biology course and as well in a 300-level neuroscience techniques course. We also investigated if the amount of sleep the previous night would impact performance changes, but this was found to have no effect. Our 5-minute meditation activity taught with the learning-cycle approach can be quickly added to any neuroscience, biology, behavior, or psychology course. Further discussion focuses on the stress response, the neurophysiology of meditation, brain electrical activity, brain regions, and impact of behaviors on physiology.

11. Introduction

Undergraduate students, especially first year (Cooke et al., 2006; Farnill & Robertson, 1990) and minority students including ethnic minorities (Paukert et al., 2006; Wei et al., 2010), transgender students (Effrig et al., 2011; Swanbrow Becker et al., 2017) and first generation students (Jenkins et al., 2013; Stephens et al., 2012), experience a large amount of anxiety and stress when transitioning to college. College is a new social and geographical environment that is often accompanied by large amounts of stress, more than that experienced by non-college attending peers (Stallman, 2010). Stress is pervasive and highly detrimental to class performance (Ahmed & Julius, 2015; Stallman, 2010; Struthers et al., 2000), something all academics know too well. The stress response also increases aging (Epel & Lithgow, 2014; Lupien et al., 1999), disease (Cohen et al., 2007; Krantz & McCeney, 2002), and prevalence of psychological disorders (Mounsey et al., 2013; Nagurney, 2007). Meditation has been shown in various contexts to decrease stress (Burger & Lockhart, 2017; Dillbeck & Orme-Johnson, 1987; Mohan et al., 2011; Singh et al., 2012; Smith, 1976; Tang et al., 2007). Teaching meditation to students can take place in multiple ways, but this study focuses on a brief introduction to meditation and the neurophysiological changes it can elicit, even in first time meditators.

As a time of intense stress, being in college also provides an opportunity to learn new life skills and stress reduction techniques. On average, college students are generally more open to meditation, since they use complementary and alternative medicine at a higher rate than the overall American population (Nowak & Hale, 2012; Versnik Nowak et al., 2015). Meditation is not new to college classrooms, but most uses of meditation have interventions that span weeks or a whole semester. These long-term interventions have successfully helped these students decrease their stress response (Ramler et al., 2015) and improve in multiple areas of life, including increased healthy habits (Soriano-Ayala et al., 2020), better psychological wellbeing and increased compassion (Crowley & Munk, 2017). Meditation has also been used to improve classroom performance as a method of self-reflection and led to better retention of classroom material (Levit Binnun & Tarrasch, 2014). Study group interventions that practice 10-minutes of meditation at the start and end of their study time had significantly higher semester and cumulative GPAs compared to a studying only control group (Hall, 1999). For further reading, meditation in the collegiate context has been thoroughly reviewed by (Shapiro et al., 2008).

We believe that meditation, when used in the classroom can not only teach students a new technique but can be a good introduction to neurophysiology and brain neuronal dynamics. Meditation has been successfully integrated into a semester long course, Neuroscience of Meditation (Olson, 2018). This course included many types of meditation, brain dissections, performance measures, EEG, and psychological questionnaires. These students experienced a reduced barrier to meditation and had an improvement of attitudes toward science in general, through the study of meditation (Olson, 2018). This course showed promising results but requires an entire semester of work. For many neuroscience, psychology, or physiology courses, this may not be possible. Our exercise aims to expose students to meditation in a single class session and show the short-term impact meditation can have on their physiology.

The University of Kentucky's STEMCats program is a living learning program for first year students in STEM fields that are planning to pursue professional STEM careers, such as medicine, dentistry, pharmacy, engineering, and research. This program provides social, academic, and professional development opportunities for success in these programs. One special course for those in the STEMCats program is the fall Biology 101 in which students explore opportunities, research, and career paths in a variety of STEM fields. During these sessions, faculty and professionals are guest speakers about their particular field to provide information and activities. We took this opportunity to develop our meditation activity and to teach the neurophysiology of meditation to these students.

Students are more interested in a topic if they have first person experience with it. A learning-cycle approach is a widely used teaching method to increase student engagement and retention of material (Kolb & Fry, 1974; Kolb, 1984) and has been specifically applied to neuroscience courses (Stewart & Stavrianeas, 2008). We used this teaching method to first engage with a problem, explore interpretations, conduct the meditation experiment, and explain the results. For the learning-cycle approach to work to link meditation and neurophysiology, we needed an experiment that included a measure that is impacted by a single session of meditation. A previous study completed by our lab showed that a longer 40-minute meditation had an acute impact on psychomotor vigilance (Kaul et al., 2010). The psychomotor vigilance task (PVT) measures reaction time and sustained attention in response to a visual stimulus (Dorrian et al., 2005). Kaul and colleagues also showed that the performance boost due to meditation may also be related to previous nights' sleep duration, so sleep data was gathered from students (Kaul et al., 2010). PVT performance is known to be susceptible to sleep loss (Kohler et al., 2017) and may be impacted by long meditation experience (Kaul et al., 2010).

The goal of this study is to show the effectiveness of a short meditation activity in the classroom. We wanted to determine if performance boosts are measurable from a short 5-minute meditation period, using a computer-based PVT program that is readily accessible for a wide variety of courses and teaching activities.

12. Materials and Methods

Our session was a 50-minute activity that included a 15-20 minute lecture, discussion on experimental design, meditation exercise, data collection, and discussion of data. All research protocols were reviewed and approved by the University of Kentucky's Institutional Review Board.

Learning objectives:

- Recognize the extraordinary claims about meditation
- Demonstrate within subject experimental design
- Interpret human reaction time data
- Describe the impact of sleep loss and meditation on reaction time

Subjects

All subjects (n=419) were students enrolled in the STEMCats class, BIO 199, which gives undergraduates a chance to be exposed to a diversity of STEM fields and research through lectures and activities with multiple faculty and researchers at the University of Kentucky.

Lecture Design

Using the learning-cycle approach we designed an experiential activity and lecture for first-year undergraduates. We first introduce the topic of meditation, explaining the history of meditation traditions, types of meditation, and end with an open-ended question on the claimed benefits of meditation (including anti-aging, anti-hypertensive, relaxation, decreased depression, helps insomnia). This introduction leads to a class-wide discussion about how meditation affects performance and how this can be tested in a classroom setting.

Next the class had a brief discussion about the potential benefits of meditation and what the students already know about meditation. This led the entire class to think about what meditation can do and how we can measure changes in some variable. During this time, the discussion was led to get students to talk about the materials that we have at our disposal including a group of novice meditators and a performance measure (the PVT). At this time an overview of the experiment was given students will complete a PVT, do the meditation activity, and take a post-meditation PVT.

PVT was completed using an online 2-minute Psychomotor Vigilance Test from the Sleep Disorders Center Florida http://www.sleepdisordersflorida.com/ pvt1.html). This is available for all internet enabled devices. For the purposes of this class, PVT was completed in a computer lab with desktop computers that each had a dedicated corded "mouse" to click. Steps were taken to ensure that PVTs are taken using the same device within subjects to reduce inter-test variability. Students were then asked to record their average response time, which is automatically calculated via the website (false starts are automatically removed, as are response times less than 100 msec - which is faster than humans can respond to a real visual stimulus). Data was recorded using a slip of paper that includes: Sleep Duration Last Night (hours), Before Meditation average response time (msec) and number of false starts, After Meditation average response time (msec) and number of false starts.

After the pre-meditation PVT data was recorded, students were instructed how to do the 5-minute focused breathing meditation. During meditation, subjects are asked to close their eyes, then focus on their breathing, and if their minds wander to bring focus back to their breath. Each trial was completed with the same meditation instruction:

> "We will now begin the focused breathing meditation. Everyone sit up straight in your chair with your feet flat on the ground. Place your hands in your lap or in a comfortable position. During this meditation, focus only on your breathing. Close your eyes and I will tell you when 5 minutes is over. Begin."

After completing the full experimental protocol, students are presented with some data that was gathered previously to discuss data analysis. Students were asked to form a conclusion on said data. During this time, discussion was led to determine how performance variables could be assessed, explaining the basics - such as a lower number indicates a faster reaction time, within vs. between group differences, and how meditation might potentially improve their reaction time. This then leads into a further short lecture/presentation on what meditation is doing to your brain, basics of electroencephalography (EEG), brain regions, and the other impacts of meditation. Meditation practices have been extensively shown to cause changes in the EEG, general physiology, anatomy, and cognitive performance.

Analysis

Since this lesson gathered sleep and reaction time data, this allowed for us to investigate this group of novice meditators' responses from a 5-minute meditation period on subsequent PVT performance. To determine performance changes due to the 5-minute meditation, the difference between pre-meditation reaction time (RT) and post-meditation RT was calculated for all subjects. A paired t-test was used to determine significant changes in reaction time ($\alpha=0.05$). Group differences between the meditation and control groups was determined using a two-sample unequal variance t-test. A bivariate fit of hours of sleep the night before testing and the change in reaction time was used to determine if the previous night sleep correlated with the change reaction time.

All statistical analysis was completed using SPSS.

13. Results

Out of the entire data set (n=417), two subjects were outliers with change in RT > 1000 msec were removed for a final sample size of n=415. There was a significant improvement in RT (t(416) = 6.73, p<0.0001) with subjects showing a mean of 26.03 ± 79.02 msec improvement in reaction time after meditation. 65.8% of people in this study had improved reaction times after the 5-minute meditation session (Figure 3.1). Sleep time before meditating, in this sample, did not correlate with change in reaction time in the control group (p=0.93) or the meditating group (p=0.21).

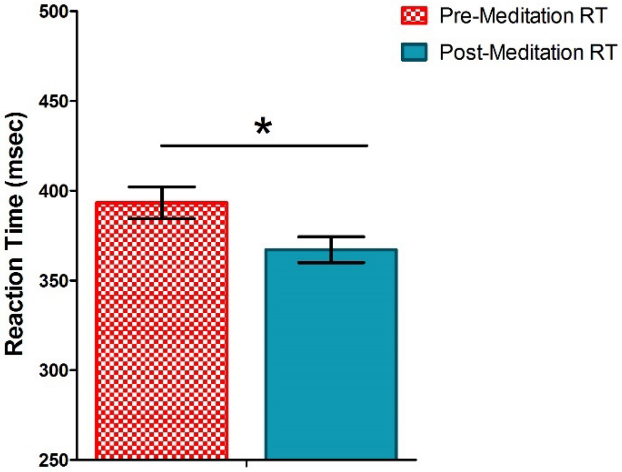


Figure 3-1 Quick 5-Minute Meditation Improves PVT Reaction Time.
Performance improved, on average, following the 5-minute meditation session when all subjects were analyzed together. Reaction time decreased an average of 26 milliseconds from pre-meditation to post-meditation (n=417). Error bars denote SEM. *p<0.001 using paired t-test.

3.1.1 2015-2016

The first data was collected during the 2015-16 STEMCats Seminar Courses. This group consisted of 186 students. Analysis was completed to determine if students got a boost in performance from the 5-minute meditation. These reaction times (RT) were measured using a 2-minute PVT and analysis was completed for the reaction time data. A one-tailed paired t-test showed a significant difference between pre and post meditation RT(t(185)=4.227, $p<0.001$) (Figure 3.2). RT decreased an average of 13.2 msec from premeditation (335 ± 71.8 msec) to post meditation (321 ± 61.9 msec). This shows that there was a significant and consistent decrease in reaction time after students underwent five minutes of meditation. From premeditation to post meditation, 122 out of 186 people improved their reaction times.

3.1.2 2016-17

The next set of data was collected in 2016-2017 and consisted of 102 students. These students also showed an improvement in RT pre versus post meditation (t(101) = 4.882, $p<0.0001$) (Figure 3.2). Reaction time decreased an average of 59.57 msec from premeditation (555 ± 281.9 msec) to post meditation (495 ± 227.9 msec). From premeditation to post meditation, 71 out of 102 people improved their RTs.

3.1.3 2018-19

A year after the last group, in 2018-2019, 41 students performed the test. This group also showed significant improvement in RT post mediation (t(40) = 1.925, $p=0.0308$) (Figure 3.2). RT decreased an average of 7.46 msec from premeditation (304

± 33.8 msec) to post-meditation (297 ± 24.8 msec). From premeditation to post meditation, 21 of 41 people improved their reaction times.

3.1.4 2019

To conclude the study, in 2019 a group started with a 5-minute control sedentary activity, followed by the 5-minute meditation protocol. To determine if reaction time differences significantly differed between meditation and the control sedentary activity, a

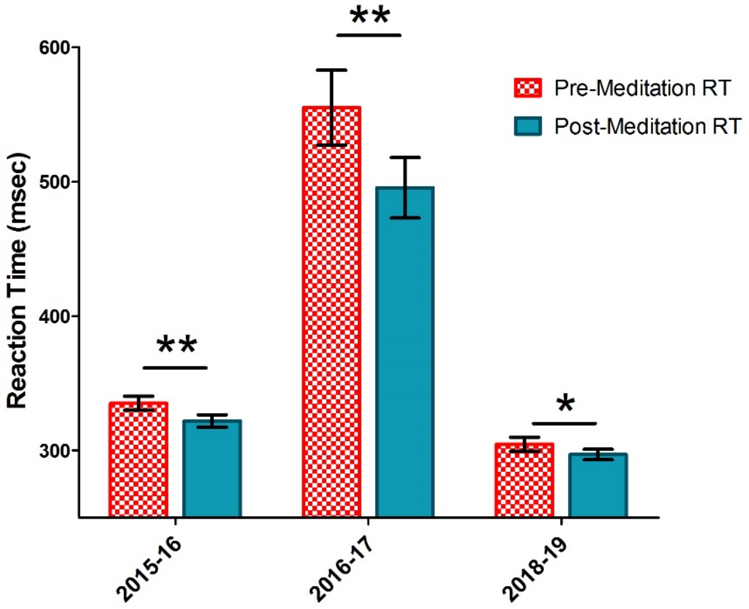


Figure 3-2 Each Group Shows an Improvement in PVT Reaction Time After 5-minutes of Meditation.

Each group of students show a significant improvement in RT after their short meditation. RT decreased in the 2015-2016 group by 13.25 msec, in the 2016-2017 group by 59.57 msec, and in the 2018-2019 group by 7.463 msecs. Error bars denote SEM. *p<0.05, **p<0.0001 using a paired t-test. *Note: We do not know the cause of the slower reaction times in 2016-2017, but this website based version may respond slower than the traditional PVT machines, or various PC based program that are equivalent, and may have had an especially slow connection in this one year. However, the delay appeared to be consistent throughout this year, and thus should not impact the pre vs. post comparisons.*

(n=72) and all meditation subjects. Two-sample unequal variance t-test was performed on the difference between control

Despite the greater RT improvement with meditation vs. control activity (26msec vs. 15msec), there were no statistically significant differences between the control activity and meditation.

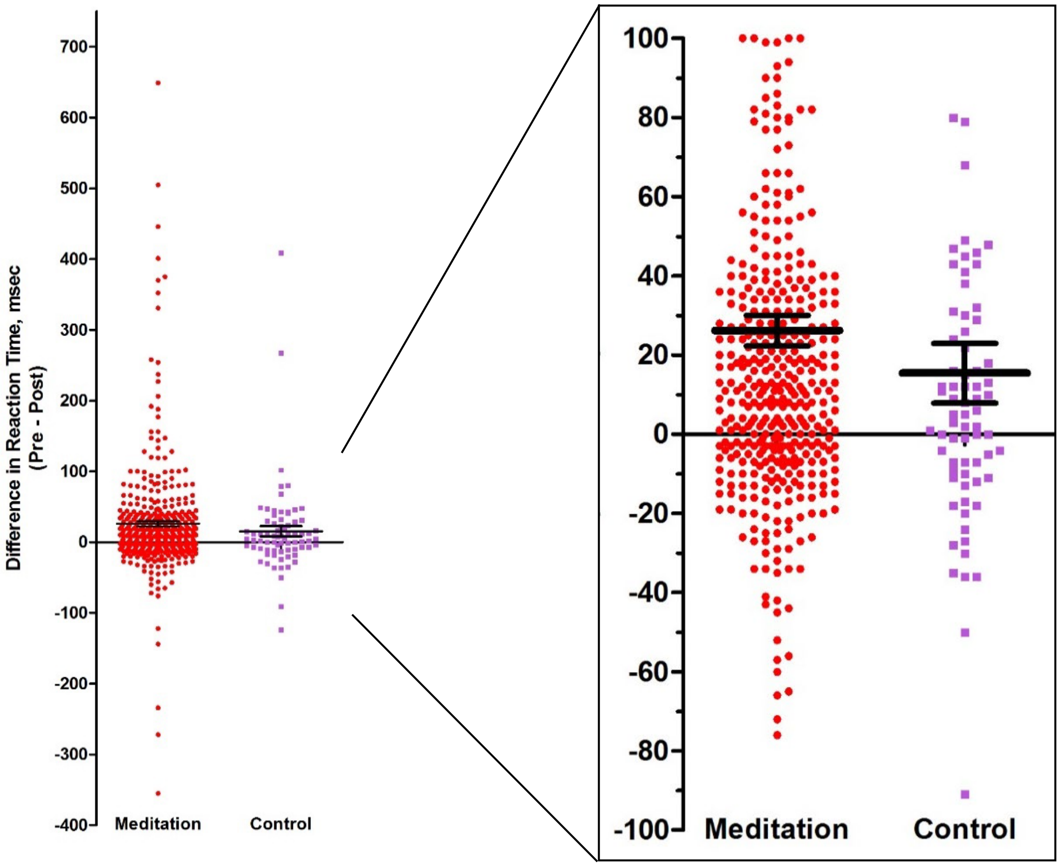


Figure 3-3 Reaction Time is Improved by both Meditation and Short Sedentary Activity. Both the control sedentary activity and meditation showed a decrease in RT. Meditation practice did show a 26 ± 79.2 msec reduction/ boost in reaction time from premeditation to post meditation for all subjects. The control activity is not dissimilar from some meditation practices and also showed a 15 ± 7.57 msec reduction of reaction time from pre activity to post control (p<0.005). Error bars denote SEM.

Follow up analysis showed that the control sedentary activity also significantly improved RT (t(71) = 3.41, p<0.0005). RT decreased from the sedentary activity an average of 15 msec from pre-activity (363 ± 98.5 msec) to post control (347 ± 81.5 msec) (Figure 3.3).

14. Discussion

3.1.5 Problem

Our data show the effectiveness of a 5-minute introductory meditation exercise and its impact on reaction time as measured by a simple PVT. This activity requires little equipment and can be broadly used as an experiment to get students interested in their control over their own brain. Previous studies of meditation in the classroom have relied on long meditation training and semester long laboratory classes. These require much effort, laboratory materials, and student input. For wider, classroom applications we show the effectiveness of only a 5-minute meditation on basic attentional performance. The online PVT is easy for students to take using any device and can be completed at home if needed. Our activity can be used in introduction biology courses, neuroscience courses, seminars, behavioral classes, and psychology courses. This activity is quick with consistently positive responses from students. This student response was not quantified, but in early years of these studies, students were able to choose different activities, and this activity had the highest attendance and highest interest (out of 12).

3.1.6 Contributions

Previous research has shown that longer training of meditation improves performance. This is the first paper that shows that 5 minutes of focused breathing meditation is effective in reducing reaction time in a large classroom study. Although data is limited to RT, this is still encouraging for future meditation research. Using the same type of meditation, a previous study completed in our lab showed that a 40-minute meditation also significantly improved RT (Kaul et al., 2010). These data showed that participants' RT decreased by 16.5 msec, which was a slightly larger boost than that seen in this study (Kaul et al., 2010), and essentially all subjects had at least a small improvement when averaged over two trials each. Thus, a longer duration of meditation appears to provide a more consistent boost in performance, however, the short 5-minute meditation often provided a similar (but slightly lower) improvement, and likely a similar physiological response.

Interestingly, the 5-minute "control" activity was also shown to have a performance boost. The act of meditation consisted of closing eyes in a controlled position. Meditation is also a time of sitting quietly, being removed from stress of academic activities, and not focusing on learning or other activities. These same things took place during the control activity, and we would even argue that this time of relaxation and sitting quietly is similar to meditation in several aspects, and perhaps allows the brain to "reset" to better perform in subsequent tasks (perhaps also similar to so-called 'power naps' of 5-10 minutes duration, that may or may not involve any actual sleep).

When discussing these data and your findings with your students, this can lead to discussions of the mechanism of action of meditation, which we and many others believe is increasing the neuronal coordination and inducing slower firing of the neurons (Cahn & Polich, 2013; Chamandeep Kaur & Preeti Singh, 2015; Lee et al., 2018). This in turn leads to the performance enhancing effect (reviewed in (Guerriero & O'Hara, 2019). Studies of longer durations of meditation with subsequent EEG recordings show that meditation can reduce attentional blink and allows for more effective brain resource allocations (Slagter et al., 2009). Other EEG studies have also shown that after meditation practice, meditation can have an immediate effect on attentional measures (Rani & Rao, 2000).

3.1.7 Limitations

This study only analyzes the effect of 5 minutes of meditation on a single performance measure, psychomotor vigilance. Other performance measures have been found to benefit from longer meditation, but it's unknown if 5 minutes of meditation would change performance on these other measures. Longer-term meditation has been shown to improve information processing, memory, and other measures of attention (reviewed in (Guerriero & O'Hara, 2019; Shapiro et al., 2008) and these require follow up studies.

Our data show no impact of self-reported sleep duration on reaction time. Due to the exploratory nature of our data, this was not unexpected. Normal sleep may show no effect due to meditation. A previous study completed by our lab (Kaul et al., 2010) showed that after a full night of sleep deprivation there was a larger boost in reaction time performance by meditation, due to the slower reaction time pre-intervention for these sleep deprived subjects. Another study of attention and meditation after one night of sleep loss showed that those subjects that meditated had better attentional performance than those who rested (Kohler et al., 2017). Both studies show the impact of an entire night sleep loss on attention that is then improved by meditation. This finding may be limited to severe sleep deprivation and was unable to be seen in the sleep amounts reported by students, which cover a more modest level of sleep debt. Our 2-minute PVT may also not be sensitive enough to capture sleep loss induced attentional deficits, as both previous studies used the more widely accepted and validated 10-minute PVT (Kaul et al., 2010; Kohler et al., 2017). This topic of sleep and meditation should undergo further study because undergraduate students in general suffer from poor sleep which can interact with missing classes, receiving lower grades, and poor mental wellness (Orzech et al., 2011). Lastly, as noted in the Figure 3.2 legend, the 2 minute website version used in this study appears to have a delay relative to the commonly used PVT-192 device that has been sold for decades, or equivalent PC versions (Khitrov et al., 2014), which typically use 10-minute test periods. However, the delay appears to be consistent within each subject and testing period, and thus our pre vs. post RT averages, and the subtraction of these values to assess increased or decreased speed should be accurate.

3.1.8 Implications

We showed that 5 minutes of meditation significantly decreased RT in the context of an introductory seminar-based class for biology majors. Beyond exposure to neuroscience through meditation, the exposure to meditation is valuable to students. As stated earlier, there is a myriad of psychological and physiological benefits from meditation practice itself.

Students can change a physiological measure, psychomotor vigilance and attention, by a very simple and short meditation. We have previously described the impact of meditation on performance (Guerriero & O'Hara, 2019) and this material is a good starting point for additional lecture and lab material. The authors also had success using this activity in a Bio 300 level course for Neuroscience majors: Introduction to Neuroscience Techniques (mostly sophomores and juniors). The meditation activity was used as a preface to an EEG-based exploratory lab. This lab included this same meditation activity (data not collected for research purposes) and followed with a brief lecture on the neurobiology of meditation and the different frequency brain waves typically demarcated in EEG studies (delta, theta, alpha, beta, and gamma). Lab groups then used an EEG to visualize the immediate eyes closed occipital alpha power increase (unpublished data). They then increased alpha power while repeating the focused breathing meditation and/or relaxation. Multiple students have stated that this lab was one of their favorites in the course due to the personal and hands on nature of the activity.

CHAPTER 4. CONCLUSIONS

In this dissertation, I aimed to determine if a single bout of meditation improves attentional performance in non-meditators. Other studies showed that short trainings of a few weeks of meditation improved reaction time and other attentional performance, but there is limited data on what a single session can do. A previous study in our lab found a 40-minute session of focused-attention meditation improved PVT reaction time, but this session may be too long for most non-meditators and those with limited time. To further understand how meditation impacts performance, I studied the impact of 20-minutes of meditation on the psychomotor vigilance test (PVT). Our data support that a single session of meditation can improve reaction time speed and vigilance in non-meditators. Our data also show that meditation lessened the number of lapses of attention during the 10-minute PVT. Finally, meditation also allowed subjects to sustain their vigilance better throughout the PVT.

To understand how meditation relates to this performance boost, I studied cortical neural dynamics using electroencephalography (EEG) in a subset of our subjects. I described cortical synchronization using a method new to the meditation field, mean phase coherence. This analysis relies on phase synchronization which is a more accurate measure of coherence than power correlation, as has been used throughout the meditation field. The subjects had high alpha coherence in their frontal electrodes, both within and between hemispheres, a measure associated with attention regulation. I also found moderate theta and beta coherence in these frontal regions. Correlations of EEG power and coherence to performance changes were then done to determine what during meditation is causing variations in performance. Better PVT performance was correlated with higher frontal alpha power, higher occipital alpha power, higher frontal beta power, and lower prefrontal gamma power. Higher alpha MPC in the frontal-temporal, frontal-occipital, and temporal-occipital regions was also correlated with better PVT performance. MPC needs to be applied to expert meditators and other meditation practices for better understanding of coherence.

I then wanted to understand if a shorter bout of meditation could improve reaction time in novices, specifically targeted for first year students. I also worked to design a classroom activity around meditation that would get students engaged with the topic and be interested in the biological study of meditation. Using the learning-cycle approach, a 50-minute activity was designed to get students to ask critical questions, engage as a test subject, analyze data, interpret the possible implications of the data, understand within subject research design, and ask bigger questions about meditation and the conscious control of cognition on their own performance. After developing this activity over a few years, only 5 minutes of meditation was found to significantly improve PVT performance in the classroom. These results reproduced over multiple years of running the activity with multiple groups of students. Attempts at developing an eyes-open control were unsuccessful, as students who were sitting and relaxing at their desks also saw a performance boost.

Future work in this field needs to better understand what is taking place in the brain during meditation and how it relates to performance. My data were correlative in identifying EEG power and coherence changes associated with PVT performance. The implications of these data is unclear. The most well understood coherence is the delta power that takes place during deep sleep (citation). Current understandings implicate that the delta wave power is associated with increase perfusion of cortical tissue by cerebral spinal fluid (CSF) that works to clear the brain of metabolic waste (Xie et al., 2013)This process, called the glymphatic system, seems to have a proportional relationship between the power of delta wave and amount of glympathic influs. Although not understood well, EEG waves of other frequencies could indicate movement of CSF during wake. It is possible that during meditation, there is a increase in this perfusion of CSF into the brain tissue, as measured in increased magnitude of alpha and theta waves, providing the restorative and performance inducing benefits due to meditation practice. If true, this would also support that a single session of meditation can impact performance.

To understand if increasing the magnitude of a specific wave can impart similar benefits of meditation, subjects could do a selective training of specific neural dynamics. This could be possible by using neural feedback, a method to train a defined brain pattern using positive reinforcement (citation). Specifically rewarding subjects with increase magnitude of frontal and posterior alpha waves, and frontal theta waves could mimic the brain wave patterns of the novice meditators that we found to perform better on the PVT. This would help elucidate the causative relationship between neural dynamics during meditation and performance could be elucidated.

Next, we were limited in the number of subjects that underwent EEG analysis, and all were pulled from the college population. First year college students have been found to… Future work should also determine certain groups attitudes toward meditation and if that impacts the performance enhancing benefits. Specifically, previous exposure to meditation from your family could shape current attitudes on practicing meditation, and therefore amount of focus given during practice. Subjects amount of stress could also impact how much they benefit from meditation. A small amount of stress may be able to be reduced during the meditation, but I believe large amounts of stress could prevent concentration on the meditation practice. Beyond college students, more subjects from broader groups need to be studied to see if the performance boost from meditation is more generalizable to the public.

My data point to limitations in the meditation research field. To understand what is taking place in the brain during meditation, more careful analysis methods need to be considered. If coherence is a measure of cortical synchronization and connectivity, then phase needs to be related from one cortical region to another. Also, my data support that the brain during meditation undergoes complex temporal changes and different EEG measures are associated with performance at varying times throughout the meditation. This raises many questions into how specifically power and MPC relate to performance and how does that change over time. In any case, my findings raise many more questions that need further investigation.

APPENDIX – SUPPLEMENTARY DATA

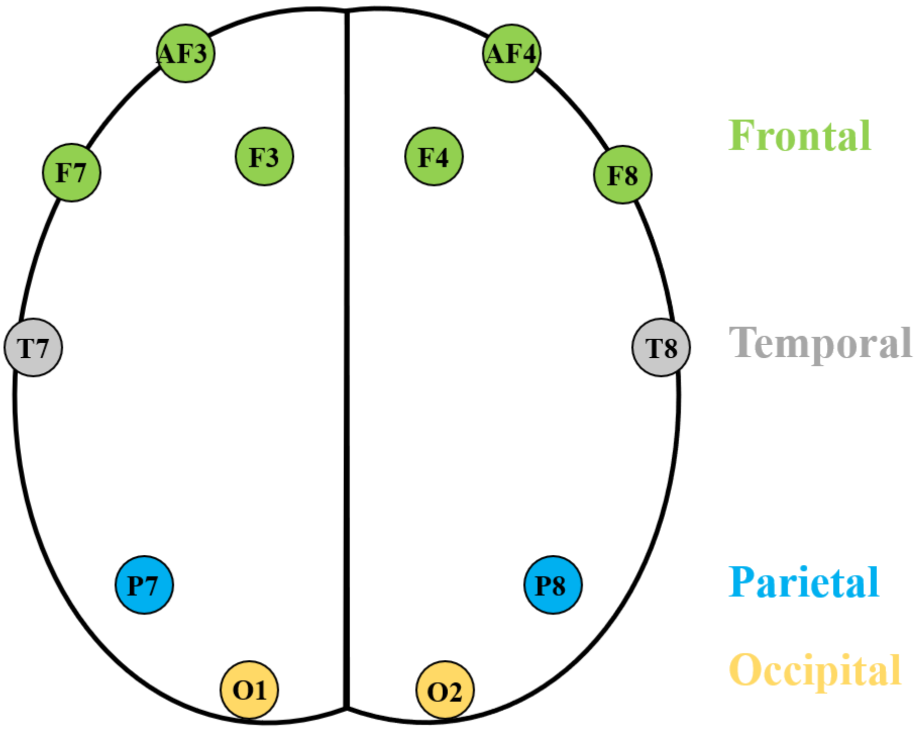


Figure 4-1 Electrode Locations for used in this study
Using the International 10-20, the following electrodes were measures in all EEG subjects. For coherence analysis these electrodes were then gathered into regions of interest based on cortical location (green: frontal, gray: temporal, blue: parietal, and yellow: occipital).

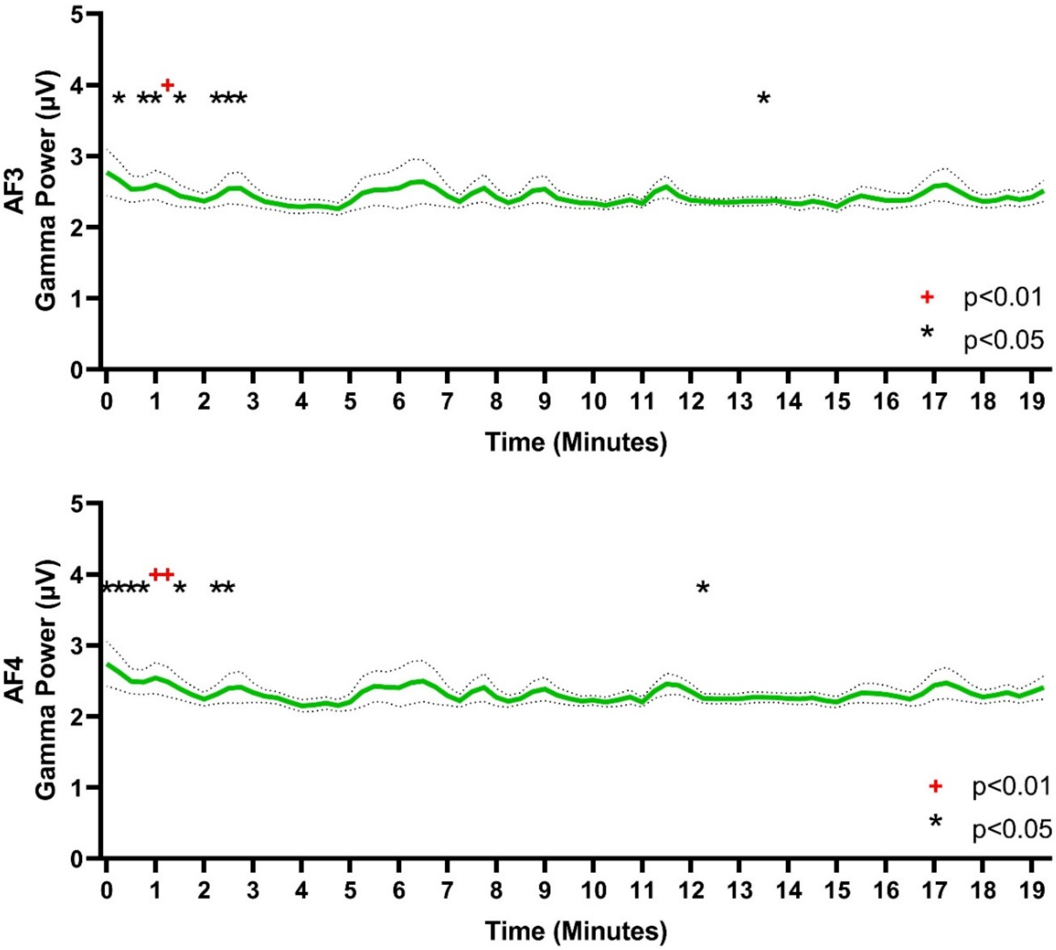
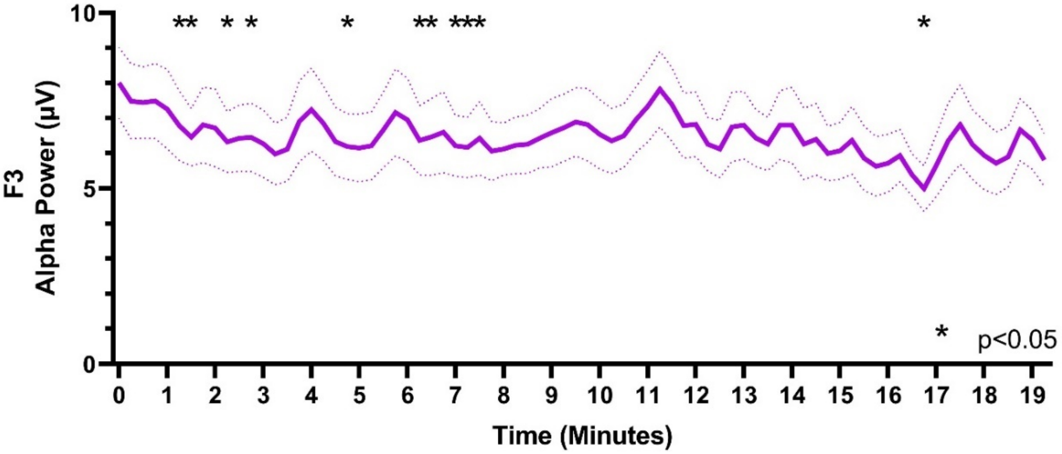


Figure 4-2 Pre-Frontal gamma power correlates with PVT performance in the beginning of meditation

Top: AF3 shows immediate correlation with PVT reaction time. The point at 13 minutes is likely noise. Bottom: AF4 also shows immediate correlation with PVT RT with a likely noise related point at 12 minutes. Solid lines indicate mean gamma power, dashed lines indicate SEM. +p<0.01, *p<0.05 Pearson's correlation of individual alpha power to difference in RT.



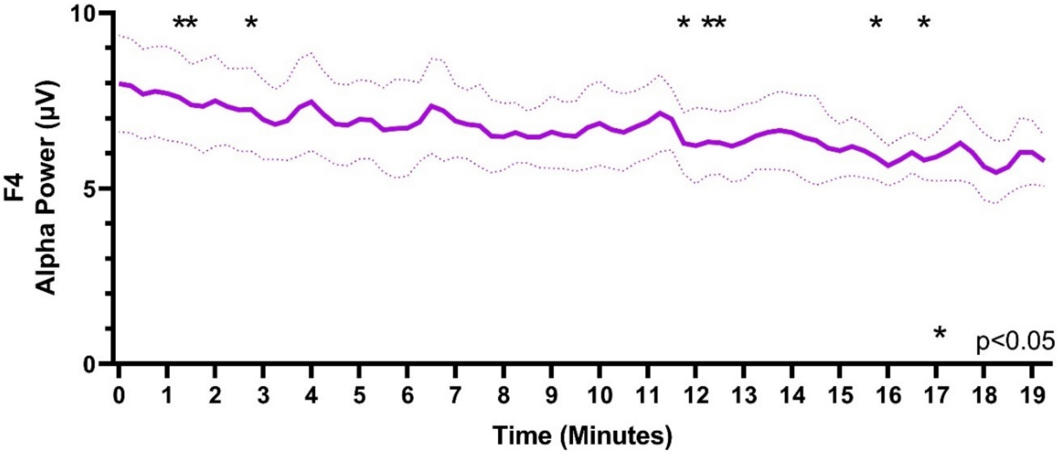


Figure 4-3 EEG frontal alpha power correlates with PVT reaction time.
Alpha power over time shows when alpha power is correlated with difference in reaction time (RT) pre-meditation minus post-meditation. The first minute lacked any correlation, but alpha power 1-8 minutes into meditation showed the most correlation to RT. Top: F3 alpha power, Bottom: F7 alpha power. Solid lines indicate mean alpha power, dashed lines indicate SEM. *p<0.05 Pearson's correlation of individual alpha power to difference in RT.

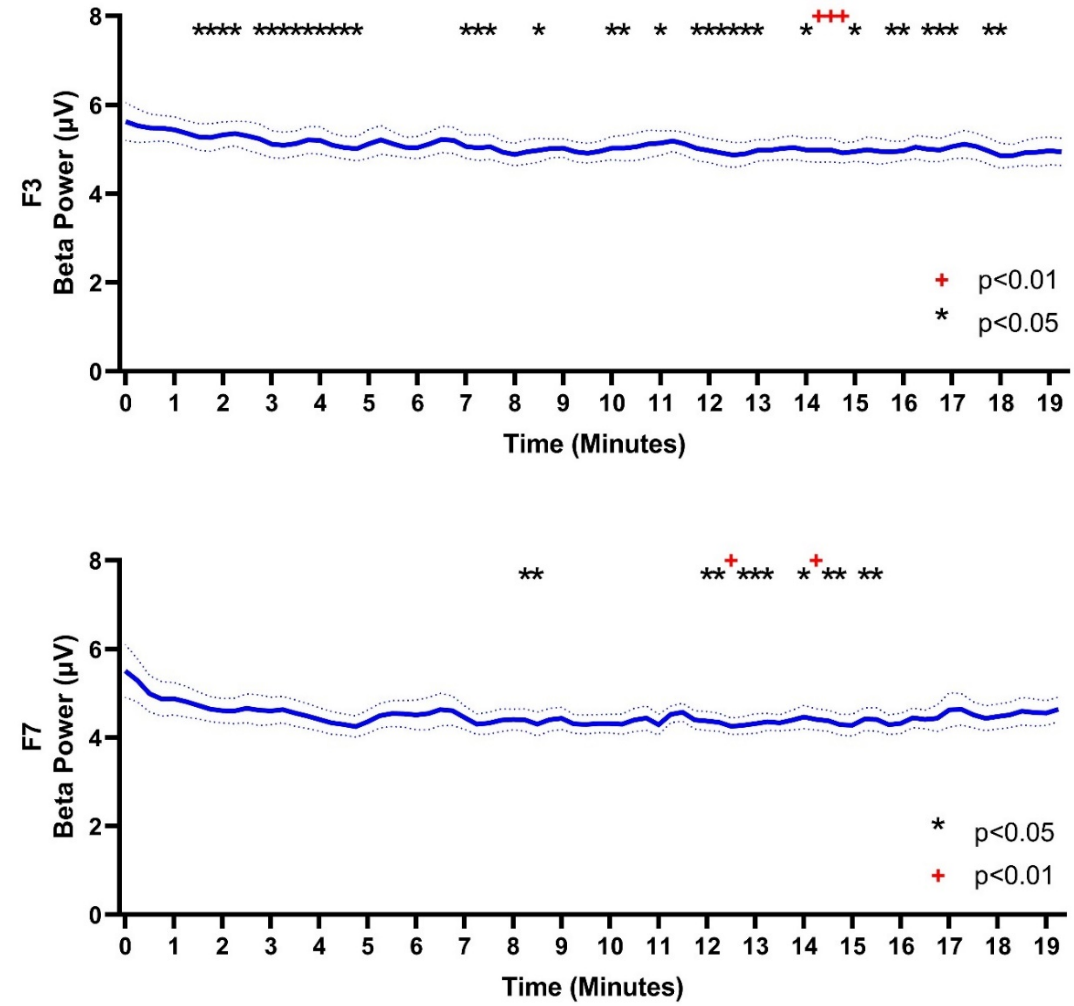


Figure 4-4 Frontal beta power correlated with performance on the PVT.
Top: F7 beta power. Bottom: F3 beta power. Solid lines indicate mean beta power, dashed lines indicate SEM. *p<0.05 Pearson's correlation of individual alpha power to difference in RT.

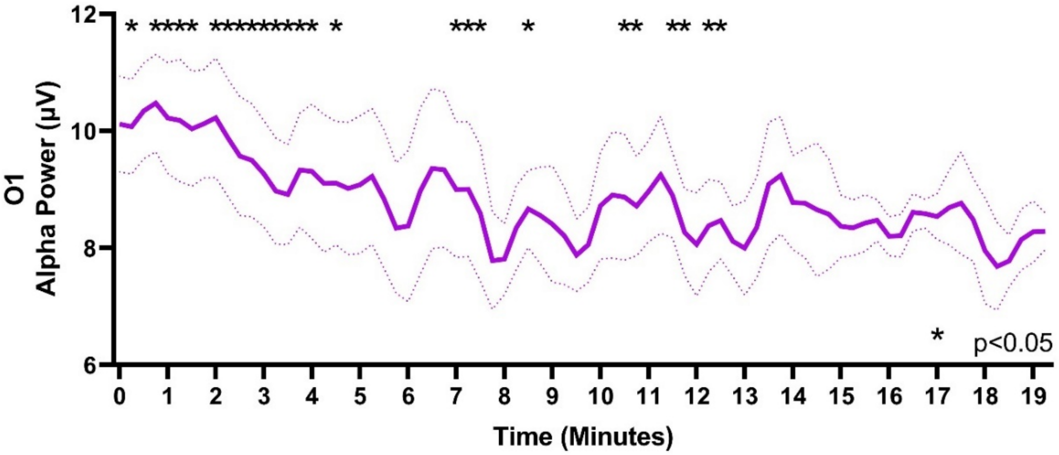


Figure 4-5 Occipital alpha power correlated with attentional performance. Supplementary Figure 5: Solid lines indicate mean alpha power, dashed lines indicate SEM. *p<0.05 Pearson's correlation of individual alpha power to difference in RT.

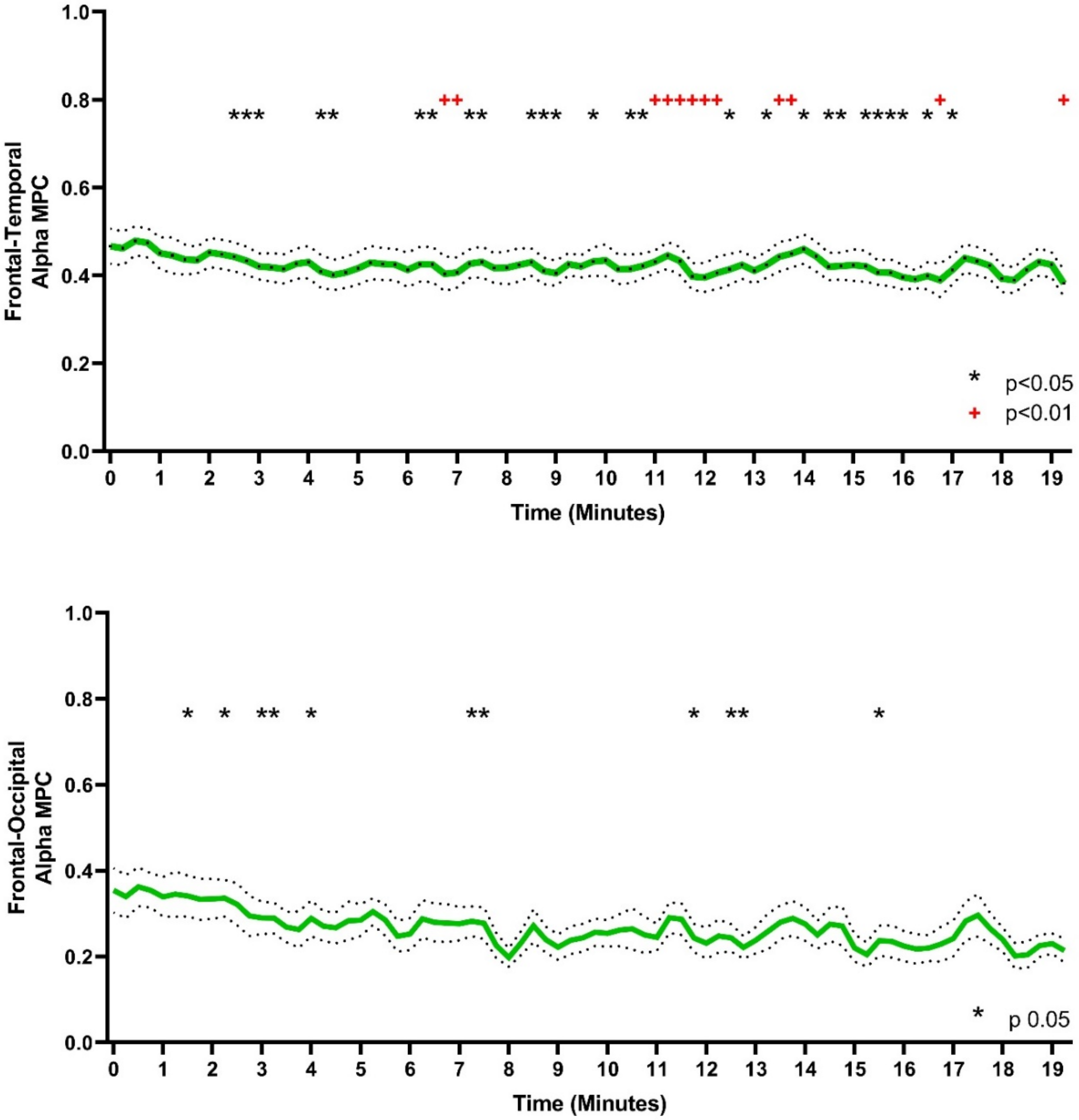


Figure 4-6 MPC was correlated with attentional performance

A) Frontal-Temporal Alpha MPC is most correlated with change in PVT performance. B) Frontal-Occipital Alpha MPC shows long distance coherence correlated with changes in PVT. Solid lines indicate mean alpha MPC, dashed lines indicate SEM. + $p<0.01$, *$p<0.05$ Pearson's correlation of individual alpha power to difference in RT.

REFERENCES

Aftanas, L., & Golocheikine, S. (2001). Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: high-resolution EEG investigation of meditation. *Neuroscience letters*, *310*(1), 57-60.

Aftanas, L. I., & Golocheikine, S. A. (2002). Non-linear dynamic complexity of the human EEG during meditation. *Neurosci Lett*, *330*(2), 143-146. https://doi.org/10.1016/s0304-3940(02)00745-0

Aftanas, L. I., & Golosheikin, S. A. (2003). Changes in cortical activity in altered states of consciousness: the study of meditation by high-resolution EEG. *Human Physiology*, *29*(2), 143-151.

Ahmed, Z., & Julius, S. H. (2015). Academic Performance, Resilience, Depression, Anxiety and Stress among Women College Students. *Indian journal of positive psychology*, *6*, 367-370.

Alexander, C. N., Langer, E. J., Newman, R. I., Chandler, H. M., & Davies, J. L. (1989). Transcendental meditation, mindfulness, and longevity: an experimental study with the elderly. *Journal of personality and social psychology*, *57*(6), 950.

Anand, B. K. C., G.S.; Singh, B. (1961). Some aspects of electroencephalograhic studies in Yogis. *Electroencephalgraphy and Clinical Neurophysiology*, *13*, 452-456.

Anderson, N. D., Lau, M. A., Segal, Z. V., & Bishop, S. R. (2007). Mindfulness-based stress reduction and attentional control. *Clinical Psychology & Psychotherapy: An International Journal of Theory & Practice*, *14*(6), 449-463.

Appelle, S., & Oswald, L. E. (1974). Simple reaction time as a function of alertness and prior mental activity. *Percept Mot Skills*, *38*(3_suppl), 1263-1268.

Arambula, P., Peper, E., Kawakami, M., & Gibney, K. H. (2001). The physiological correlates of Kundalini Yoga meditation: a study of a yoga master. *Applied psychophysiology and biofeedback*, *26*(2), 147-153.

Bagchi, B. K. W., M.A. (1958). Simultaneous EEG and Other Recordings During Some Yogic Practices. *Electroencephalography and Clinical Neurophysiology*(10), 193.

Baijal, S., & Srinivasan, N. (2010). Theta activity and meditative states: spectral changes during concentrative meditation. *Cogn Process*, *11*(1), 31-38. https://doi.org/10.1007/s10339-009-0272-0

Banquet, J. P. (1973). Spectral analysis of the EEG in meditation. *Electroencephalogr Clin Neurophysiol*, *35*(2), 143-151.

Barry, R. J., Clarke, A. R., Johnstone, S. J., Magee, C. A., & Rushby, J. A. (2007). EEG differences between eyes-closed and eyes-open resting conditions. *Clinical Neurophysiology*, *118*(12), 2765-2773. https://doi.org/https://doi.org/10.1016/j.clinph.2007.07.028

Basharpoor, S., Heidari, F., & Molavi, P. (2021). EEG coherence in theta, alpha, and beta bands in frontal regions and executive functions. *Applied Neuropsychology: Adult*, *28*(3), 310-317. https://doi.org/10.1080/23279095.2019.1632860

Basner, M., & Dinges, D. F. (2011). Maximizing sensitivity of the psychomotor vigilance test (PVT) to sleep loss. *Sleep*, *34*(5), 581-591. https://doi.org/10.1093/sleep/34.5.581

Benson, H., Steinert, R. F., Greenwood, M. M., Klemchuk, H. M., & Peterson, N. H. (1975). Continuous measurement of O2 consumption and CO2 elimination during a wakeful hypometabolic state. *Journal of human stress*, *1*(1), 37-44.

Braboszcz, C., Cahn, B. R., Levy, J., Fernandez, M., & Delorme, A. (2017). Increased gamma brainwave amplitude compared to control in three different meditation traditions. *Plos One*, *12*(1), e0170647.

Bujatti, M., & Biederer, P. (1976). Serotonin, Noradrenaline, Dopamine Metabolites in Transcendental Meditation-Technique. *J Neural Transm*, *39*(3), 257-267.

Burger, K. G., & Lockhart, J. S. (2017). Meditation's Effect on Attentional Efficiency, Stress, and Mindfulness Characteristics of Nursing Students. *Journal of Nursing Education*, *56*(7), 430-434.

Cahn, B. R., Delorme, A., & Polich, J. (2010). Occipital gamma activation during Vipassana meditation. *Cognitive processing*, *11*(1), 39-56.

Cahn, B. R., & Polich, J. (2013). Meditation states and traits: EEG, ERP, and neuroimaging studies.

Cantero, J. L., Atienza, M., & Salas, R. M. (2002). Human alpha oscillations in wakefulness, drowsiness period, and REM sleep: different electroencephalographic phenomena within the alpha band. *Neurophysiologie Clinique/Clinical Neurophysiology*, *32*(1), 54-71.

Cohen, S., Janicki-Deverts, D., & Miller, G. E. (2007). *Psychological stress and disease* [doi:10.1001/jama.298.14.1685].

Colzato, L. S., van der Wel, P., Sellaro, R., & Hommel, B. (2016). A single bout of meditation biases cognitive control but not attentional focusing: Evidence from the global-local task. *Conscious Cogn*, *39*, 1-7. https://doi.org/10.1016/j.concog.2015.11.003

Cooke, R., Bewick, B. M., Barkham, M., Bradley, M., & Audin, K. (2006). Measuring, monitoring and managing the psychological well-being of first year university students. *British Journal of Guidance & Counselling*, *34*(4), 505-517. https://doi.org/10.1080/03069880600942624

Crowley, C., & Munk, D. (2017). An Examination of the Impact of a College Level Meditation Course on College Student Well Being. *College student journal*, *51*, 91-98.

Das, N. N. G., H. (1957). Variations de l'activite electrique du cerveau du coeur et des muscles quelletiques au cours de la meditation et de l'extase yogique. . *Electroencephalgraphy and Clinical Neurophysiology*, *6*, 211-219.

Davidson, J. M. (1976). The physiology of meditation and mystical states of consciousness. *Perspect Biol Med*, *19*(3), 345-379.

Davidson, R. J., Kabat-Zinn, J., Schumacher, J., Rosenkranz, M., Muller, D., Santorelli, S. F., . . . Sheridan, J. F. (2003). Alterations in brain and immune function produced by mindfulness meditation. *Psychosomatic medicine*, *65*(4), 564-570.

Dillbeck, M. C., & Bronson, E. C. (1981). Short-Term Longitudinal Effects of the Transcendental Meditation Technique on EEG Power and Coherence. *International Journal of Neuroscience*, *14*(3-4), 147-151. https://doi.org/10.3109/00207458108985827

Dillbeck, M. C., & Orme-Johnson, D. W. (1987). Physiological differences between transcendental meditation and rest.

Dissanayaka, C., Ben-Simon, E., Gruberger, M., Maron-Katz, A., Sharon, H., Hendler, T., & Cvetkovic, D. (2015). Comparison between human awake, meditation and drowsiness EEG activities based on directed transfer function and MVDR coherence methods. *Med Biol Eng Comput*, *53*(7), 599-607. https://doi.org/10.1007/s11517-015-1272-0

Dorrian, J., Rogers, N., Dinges, D., & Kushida, C. (2005). Psychomotor vigilance performance: Neurocognitive assay sensitive to sleep loss. In C. Kushida (Ed.), *Sleep deprivation: clinical issues, pharmacology and sleep loss effects* (pp. 39-70). Marcel Dekker, Inc.

Dunn, B. R., Hartigan, J. A., & Mikulas, W. L. (1999). Concentration and mindfulness meditations: unique forms of consciousness? *Applied psychophysiology and biofeedback*, *24*(3), 147-165.

Effrig, J. C., Bieschke, K. J., & Locke, B. D. (2011). Examining victimization and psychological distress in transgender college students. *Journal of College Counseling*, *14*(2), 143-157. https://doi.org/10.1002/j.2161-1882.2011.tb00269.x

Elson, B. D., Hauri, P., & Cunis, D. (1977). Physiological changes in yoga meditation. *Psychophysiology*, *14*(1), 52-57.

Epel, E. S., & Lithgow, G. J. (2014). Stress biology and aging mechanisms: toward understanding the deep connection between adaptation to stress and longevity. *J Gerontol A Biol Sci Med Sci*, *69 Suppl 1*(Suppl 1), S10-16. https://doi.org/10.1093/gerona/glu055

Farnill, D., & Robertson, M. (1990). Sleep disturbance, tertiary-transition stress, and psychological symptoms among young first-year Australian college students. *Australian Psychologist*, *25*, 178-188.

Ferrarelli, F., Smith, R., Dentico, D., Riedner, B. A., Zennig, C., Benca, R. M., . . . Tononi, G. (2013). Experienced mindfulness meditators exhibit higher parietal-occipital EEG gamma activity during NREM sleep. *Plos One*, *8*(8), e73417.

Fries, P. (2005). A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. *Trends Cogn Sci*, *9*(10), 474-480. https://doi.org/10.1016/j.tics.2005.08.011

Fries, P. (2015). Rhythms for Cognition: Communication through Coherence. *Neuron*, *88*(1), 220-235. https://doi.org/10.1016/j.neuron.2015.09.034

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*, 680407. https://doi.org/10.1155/2012/680407

Fumoto, M., Sato-Suzuki, I., Seki, Y., Mohri, Y., & Arita, H. (2004). Appearance of high-frequency alpha band with disappearance of low-frequency alpha band in EEG is produced during voluntary abdominal breathing in an eyes-closed condition. *Neuroscience research*, *50*(4), 307-317.

Gaylord, C., Orme-Johnson, D., & Travis, F. (1989). The Effects of the Transcendental Mediation Technique and Progressive Muscle Relaxation on Eeg Coherence, Stress Reactivity, and Mental Health in Black Adults. *International Journal of Neuroscience*, *46*(1-2), 77-86. https://doi.org/10.3109/00207458908991618

Ghista, D. N., Nandagopal, D., Ramamurthi, B., Das, A., Mukherji, A., & Srinivasan, T. (1976). Physiological characterisation of the 'meditative state'during intuitional practice (the Ananda Marga system of mediation) and its therapeutic value. *Medical and Biological Engineering*, *14*(2), 209-214.

Goleman, D., & Schwartz, G. (1976). Meditation as an intervention in stress reactivity. *Journal of Consulting and Clinical Psychology*, *44*(3), 456.

Guerriero, L. E., & O'Hara, B. F. (2019). Meditation, Sleep, and Performance. In (Vol. 4). OBM Integrative and Complementary Medicine.

Hall, P. D. (1999). The Effect of Meditation on the Academic Performance of African American College Students. *Journal of Black Studies*, *29*(3), 408-415. https://doi.org/10.1177/002193479902900305

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. https://doi.org/https://doi.org/10.1016/j.neuroimage.2011.07.008

Hauswald, A., Übelacker, T., Leske, S., & Weisz, N. (2015). What it means to be Zen: Marked modulations of local and interareal synchronization during open monitoring meditation. *NeuroImage*, *108*, 265-273.

Hodgins, H. S., & Adair, K. C. (2010). Attentional processes and meditation. *Consciousness and cognition*, *19*(4), 872-878.

Holt, W. R., Caruso, J. L., & Riley, J. B. (1978). Transcendental meditation vs pseudo-meditation on visual choice reaction time. *Percept Mot Skills*.

Huang, H. Y., & Lo, P. C. (2009). EEG dynamics of experienced Zen meditation practitioners probed by complexity index and spectral measure. *J Med Eng Technol*, *33*(4), 314-321. https://doi.org/10.1080/03091900802602677

Hölzel, B. K., Carmody, J., Vangel, M., Congleton, C., Yerramsetti, S. M., Gard, T., & Lazar, S. W. (2011). Mindfulness practice leads to increases in regional brain gray matter density. *Psychiatry Research: Neuroimaging*, *191*(1), 36-43.

INANAGA, K. (1998). Frontal midline theta rhythm and mental activity. *Psychiatry and Clinical Neurosciences*, *52*(6), 555-566. https://doi.org/https://doi.org/10.1046/j.1440-1819.1998.00452.x

Janssen, L., Kan, C. C., Carpentier, P. J., Sizoo, B., Hepark, S., Grutters, J., . . . Speckens, A. E. (2015). Mindfulness based cognitive therapy versus treatment as usual in adults with attention deficit hyperactivity disorder (ADHD). *BMC psychiatry*, *15*(1), 216.

Jenkins, S., Belanger, A., Connally, M., Boals, A., & Durón, K. (2013). First-Generation Undergraduate Students' Social Support, Depression, and Life Satisfaction. *Journal of College Counseling*, *16*. https://doi.org/10.1002/j.2161-1882.2013.00032.x

Kang, D.-H., Jo, H. J., Jung, W. H., Kim, S. H., Jung, Y.-H., Choi, C.-H., . . . Kwon, J. S. (2012). The effect of meditation on brain structure: cortical thickness mapping and diffusion tensor imaging. *Social cognitive and affective neuroscience*, *8*(1), 27-33.

Kasamatsu, A., & Hirai, T. (1966). An electroencephalographic study on the zen meditation (Zazen). *Folia Psychiatr Neurol Jpn*, *20*(4), 315-336.

Kaul, P., Passafiume, J., Sargent, R. C., & O'Hara, B. F. (2010). Meditation acutely improves psychomotor vigilance, and may decrease sleep need. *Behavioral and brain Functions*, *6*(1), 47.

Kaur, C., & Singh, P. (2015). EEG derived neuronal dynamics during meditation: progress and challenges. *Advances in preventive medicine*, *2015*.

Kaur, C., & Singh, P. (2015). EEG Derived Neuronal Dynamics during Meditation: Progress and Challenges. *Adv Prev Med*, *2015*, 614723. https://doi.org/10.1155/2015/614723

Khalsa, S. S., Rudrauf, D., Damasio, A. R., Davidson, R. J., Lutz, A., & Tranel, D. (2008). Interoceptive awareness in experienced meditators. *Psychophysiology*, *45*(4), 671-677.

Khare, K., & Nigam, S. K. (2000). A study of electroencephalogram in mediators. *Indian Journal of Physiology and Pharmacology*, *44*(2), 173-178.

Khitrov, M. Y., Laxminarayan S Fau - Thorsley, D., Thorsley D Fau - Ramakrishnan, S., Ramakrishnan S Fau - Rajaraman, S., Rajaraman S Fau - Wesensten, N. J., Wesensten Nj Fau - Reifman, J., & Reifman, J. (2014). PC-PVT: a platform for psychomotor vigilance task testing, analysis, and prediction. (1554-3528 (Electronic)).

King, M. S., Carr, T., & D'Cruz, C. (2002). Transcendental meditation, hypertension and heart disease. *Australian family physician*, *31*(2), 164.

Kirschfeld, K. (2005). The physical basis of alpha waves in the electroencephalogram and the origin of the “Berger effect”. *Biological Cybernetics*, *92*(3), 177-185. https://doi.org/10.1007/s00422-005-0547-1

Kjaer, T. W., Bertelsen, C., Piccini, P., Brooks, D., Alving, J., & Lou, H. C. (2002). Increased dopamine tone during meditation-induced change of consciousness. *Cognitive Brain Research*, *13*(2), 255-259.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain research reviews*, *29*(2-3), 169-195.

Klimesch, W., Doppelmayr, M., Schimke, H., & Pachinger, T. (1996). Alpha frequency, reaction time, and the speed of processing information. *Journal of clinical neurophysiology*, *13*(6), 511-518.

Kohler, M., Rawlings, M., Kaeding, A., Banks, S., & Immink, M. A. (2017). Meditation is effective in reducing sleepiness and improving sustained attention following acute sleep restriction. *Journal of Cognitive Enhancement*, *1*(2), 210-218.

Kolb, D., & Fry, R. (1974). Toward an Applied Theory of Experiential Learning. *Theories of group process*.

Kolb, D. A. (1984). *Experiential Learning: Experience as the Source of Learning and Development*. Prentice-Hall.

Kopal, J., Vyšata, O., Burian, J., Schätz, M., Procházka, A., & Vališ, M. (2014). Complex continuous wavelet coherence for EEG microstates detection in insight and calm meditation. *Consciousness and Cognition*, *30*, 13-23. https://doi.org/https://doi.org/10.1016/j.concog.2014.07.015

Krantz, D. S., & McCeney, M. K. (2002). Effects of psychological and social factors on organic disease: a critical assessment of research on coronary heart disease. *Annu Rev Psychol*, *53*, 341-369. https://doi.org/10.1146/annurev.psych.53.100901.135208

Kubota, Y., Sato, W., Toichi, M., Murai, T., Okada, T., Hayashi, A., & Sengoku, A. (2001). Frontal midline theta rhythm is correlated with cardiac autonomic activities during the performance of an attention demanding meditation procedure. *Cognitive Brain Research*, *11*(2), 281-287.

Laghari, W. M., Baloch, M. U., Mengal, M. A., & Shah, S. J. (2014). Performance Analysis of Analog Butterworth Low Pass Filter as Compared to Chebyshev Type-I Filter, Chebyshev Type-II Filter and Elliptical Filter. *Circuits and Systems*, *Vol.05No.09*, 8, Article 49253. https://doi.org/10.4236/cs.2014.59023

Lang, R., Dehof, K., Meurer, K. A., & Kaufmann, W. (1979). Sympathetic activity and transcendental meditation. *J Neural Transm*, *44*(1-2), 117-135.

LaRocco, J., Le, M. D., & Paeng, D.-G. (2020). A Systemic Review of Available Low-Cost EEG Headsets Used for Drowsiness Detection. *Frontiers in neuroinformatics*, *14*, 553352-553352. https://doi.org/10.3389/fninf.2020.553352

Laukka, S. J., Järvilehto, T., Alexandrov, Y. I., & Lindqvist, J. (1995). Frontal midline theta related to learning in a simulated driving task. *Biological Psychology*, *40*(3), 313-320.

Lazar, S. W., Bush, G., Gollub, R. L., Fricchione, G. L., Khalsa, G., & Benson, H. (2000). Functional brain mapping of the relaxation response and meditation. *Neuroreport*, *11*(7), 1581-1585.

Lazar, S. W., Kerr, C. E., Wasserman, R. H., Gray, J. R., Greve, D. N., Treadway, M. T., . . . Benson, H. (2005). Meditation experience is associated with increased cortical thickness. *Neuroreport*, *16*(17), 1893.

Lee, D. J., Kulubya, E., Goldin, P., Goodarzi, A., & Girgis, F. (2018). Review of the Neural Oscillations Underlying Meditation. *Frontiers in neuroscience*, *12*, 178.

Levine, P. (1976). The coherence spectral array (COSPAR) and its application to the study of spatial ordering in the EEG. Proceedings of the San Diego Biomedical Symposium,

Levit Binnun, N., & Tarrasch, R. (2014). Relation between contemplative exercises and an enriched psychology students' experience in a neuroscience course. *Front Psychol*, *5*, 1296. https://doi.org/10.3389/fpsyg.2014.01296

Lippelt, D. P., Hommel, B., & Colzato, L. S. (2014). Focused attention, open monitoring and loving kindness meditation: effects on attention, conflict monitoring, and creativity - A review. *Front Psychol*, *5*, 1083. https://doi.org/10.3389/fpsyg.2014.01083

Lippelt, D. P., Hommel, B., & Colzato, L. S. (2014). Focused attention, open monitoring and loving kindness meditation: effects on attention, conflict monitoring, and creativity–A review. *Frontiers in psychology*, *5*, 1083.

Lo, P.-C., & Chang, C.-H. (2013). Spatially Nonlinear Interdependence of Alpha-Oscillatory Neural Networks under Chan Meditation. *Evidence-Based Complementary and Alternative Medicine*, *2013*, 360371. https://doi.org/10.1155/2013/360371

Lupien, S. J., Nair, N. P., Brière, S., Maheu, F., Tu, M. T., Lemay, M., . . . Meaney, M. J. (1999). Increased cortisol levels and impaired cognition in human aging: implication for depression and dementia in later life. *Rev Neurosci*, *10*(2), 117-139. https://doi.org/10.1515/revneuro.1999.10.2.117

Lutz, A., Greischar, L. L., Rawlings, N. B., Ricard, M., & Davidson, R. J. (2004). Long-term meditators self-induce high-amplitude gamma synchrony during mental practice. *Proceedings of the national Academy of Sciences*, *101*(46), 16369-16373.

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. *Journal of Neuroscience*, *29*(42), 13418-13427.

Manna, A., Raffone, A., Perrucci, M. G., Nardo, D., Ferretti, A., Tartaro, A., . . . Romani, G. L. (2010). Neural correlates of focused attention and cognitive monitoring in meditation. *Brain Res Bull*, *82*(1-2), 46-56. https://doi.org/10.1016/j.brainresbull.2010.03.001

Melloni, M., Sedeño, L., Couto, B., Reynoso, M., Gelormini, C., Favaloro, R., . . . Ibanez, A. (2013). Preliminary evidence about the effects of meditation on interoceptive sensitivity and social cognition. *Behavioral and brain Functions*, *9*(1), 47.

Miller, J. J., Fletcher, K., & Kabat-Zinn, J. (1995). Three-year follow-up and clinical implications of a mindfulness meditation-based stress reduction intervention in the treatment of anxiety disorders. *General hospital psychiatry*, *17*(3), 192-200.

Mitchell, J. T., McIntyre, E. M., English, J. S., Dennis, M. F., Beckham, J. C., & Kollins, S. H. (2017). A pilot trial of mindfulness meditation training for ADHD in adulthood: impact on core symptoms, executive functioning, and emotion dysregulation. *Journal of Attention Disorders*, *21*(13), 1105-1120.

Mizuhara, H., Wang, L.-Q., Kobayashi, K., & Yamaguchi, Y. (2004). A long-range cortical network emerging with theta oscillation in a mental task. *Neuroreport*, *15*(8), 1233-1238.

Mizuki, Y., Tanaka, M., Isozaki, H., Nishijima, H., & Inanaga, K. (1980). Periodic appearance of theta rhythm in the frontal midline area during performance of a mental task. *Electroencephalography and Clinical Neurophysiology*, *49*(3), 345-351.

Mohan, A., Sharma, R., & Bijlani, R. L. (2011). Effect of meditation on stress-induced changes in cognitive functions. *The Journal of Alternative and Complementary Medicine*, *17*(3), 207-212.

Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and cognition*, *18*(1), 176-186.

Mormann, F., Lehnertz, K., David, P., & E. Elger, C. (2000). Mean phase coherence as a measure for phase synchronization and its application to the EEG of epilepsy patients. *Physica D: Nonlinear Phenomena*, *144*(3), 358-369. https://doi.org/https://doi.org/10.1016/S0167-2789(00)00087-7

Morse, D. R., Martin, J. S., Furst, M. L., & Dubin, L. L. (1977). A physiological and subjective evaluation of meditation, hypnosis, and relaxation. *Psychosomatic medicine*, *39*(5), 304-324.

Mounsey, R., Vandehey, M. A., & Diekhoff, G. M. (2013). Working and non-working university students: anxiety, depression, and grade point average [Report]. *College Student Journal*, *47*, 379+.

Murata, T., Takahashi, T., Hamada, T., Omori, M., Kosaka, H., Yoshida, H., & Wada, Y. (2004). Individual trait anxiety levels characterizing the properties of zen meditation. *Neuropsychobiology*, *50*(2), 189-194. https://doi.org/10.1159/000079113

Nagurney, A. J. (2007). The effects of relationship stress and unmitigated communion on physical and mental health outcomes [https://doi.org/10.1002/smi.1146]. *Stress and Health*, *23*(4), 267-273. https://doi.org/https://doi.org/10.1002/smi.1146

Newandee, D. A., & Reisman, S. (1996). Measurement of the electroencephalogram (EEG) coherence in group meditation. *Proceedings of the IEEE 22nd Annual Northeast Bioengineering Conference*, 95-96.

Ng, B. S. W., Logothetis, N. K., & Kayser, C. (2012). EEG Phase Patterns Reflect the Selectivity of Neural Firing. *Cerebral Cortex*, *23*(2), 389-398. https://doi.org/10.1093/cercor/bhs031

Nielsen, L., & Kaszniak, A. W. (2006). Awareness of subtle emotional feelings: a comparison of long-term meditators and nonmeditators. *Emotion*, *6*(3), 392.

Nowak, A. L. V., & Hale, H. M. (2012). Prevalence of Complementary and Alternative Medicine Use Among U.S. College Students. *American Journal of Health Education*, *43*(2), 116-126. https://doi.org/10.1080/19325037.2012.10599227

Olson, J. D., Wander, J. D., Johnson, L., Sarma, D., Weaver, K., Novotny, E. J., . . . Darvas, F. (2016). Comparison of subdural and subgaleal recordings of cortical high-gamma activity in humans. *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*, *127*(1), 277-284. https://doi.org/10.1016/j.clinph.2015.03.014

Olson, L. E. (2018). Impact of Experiential Neuroscience of Meditation Course on Attitudes Toward Meditation and Science. *Journal of undergraduate neuroscience education : JUNE : a publication of FUN, Faculty for Undergraduate Neuroscience*, *17 1*, A59-A66.

Orme-Johnson, D. W., & Haynes, C. T. (1981). EEG phase coherence, pure consciousness, creativity, and TM—Sidhi experiences. *International Journal of Neuroscience*, *13*(4), 211-217.

Orme-Johnson, D. W., Schneider, R. H., Son, Y. D., Nidich, S., & Cho, Z. H. (2006). Neuroimaging of meditation's effect on brain reactivity to pain. *Neuroreport*, *17*(12), 1359-1363. https://doi.org/10.1097/01.wnr.0000233094.67289.a8

Orzech, K. M., Salafsky, D. B., & Hamilton, L. A. (2011). The state of sleep among college students at a large public university. *J Am Coll Health*, *59*(7), 612-619. https://doi.org/10.1080/07448481.2010.520051

Pace, T. W., Negi, L. T., Adame, D. D., Cole, S. P., Sivilli, T. I., Brown, T. D., . . . Raison, C. L. (2009). Effect of compassion meditation on neuroendocrine, innate immune and behavioral responses to psychosocial stress. *Psychoneuroendocrinology*, *34*(1), 87-98.

Pagnoni, G., & Cekic, M. (2007). Age effects on gray matter volume and attentional performance in Zen meditation. *Neurobiology of aging*, *28*(10), 1623-1627.

Park, Y. J., & Park, Y. B. (2012). Clinical utility of paced breathing as a concentration meditation practice. *Complement Ther Med*, *20*(6), 393-399. https://doi.org/10.1016/j.ctim.2012.07.008

Paukert, A., Pettit, J., Perez, M., & Walker, R. (2006). Affective and Attributional Features of Acculturative Stress Among Ethnic Minority College Students. *The Journal of psychology*, *140*, 405-419. https://doi.org/10.3200/JRLP.140.5.405-419

Puryear, H. B., Cayce, C. T., & Thurston, M. A. (1976). Anxiety reduction associated with meditation: home study. *Percept Mot Skills*, *42*(43), 527-531.

Ramler, T., Tennison, L., Lynch, J., & Murphy, P. (2015). Mindfulness and the College Transition: The Efficacy of an Adapted Mindfulness-Based Stress Reduction

Intervention in Fostering Adjustment among First-Year Students. *Mindfulness*, *7*. https://doi.org/10.1007/s12671-015-0398-3

Rani, N., & Rao, P. V. K. (2000). Effects of meditation on attention processes.

Sarnthein, J., Petsche, H., Rappelsberger, P., Shaw, G., & Von Stein, A. (1998). Synchronization between prefrontal and posterior association cortex during human working memory. *Proceedings of the National Academy of Sciences*, *95*(12), 7092-7096.

Schevon, C. A., Cappell, J., Emerson, R., Isler, J., Grieve, P., Goodman, R., . . . Gilliam, F. (2007). Cortical abnormalities in epilepsy revealed by local EEG synchrony. *NeuroImage*, *35*(1), 140-148. https://doi.org/https://doi.org/10.1016/j.neuroimage.2006.11.009

Schürmann, M., & Başar, E. (2001). Functional aspects of alpha oscillations in the EEG. *International Journal of Psychophysiology*, *39*(2-3), 151-158.

Shapiro, S., Brown, K., & Astin, J. (2008). Toward the Integration of Meditation into Higher Education: A Review of Research Evidence. *Teachers College Record*, *113*.

Simmonds, D. J., Pekar, J. J., & Mostofsky, S. H. (2008). Meta-analysis of Go/No-go tasks demonstrating that fMRI activation associated with response inhibition is task-dependent. *Neuropsychologia*, *46*(1), 224-232.

Singh, Y., Sharma, R., & Talwar, A. (2012). Immediate and Long-term Effects of Meditation on Acute Stress Reactivity, Cognitive Functions, and Intelligence. *Alternative therapies in health and medicine*, *18*(6).

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

Slagter, H. A., Lutz, A., Greischar, L. L., Nieuwenhuis, S., & Davidson, R. J. (2009). Theta phase synchrony and conscious target perception: impact of intensive mental training. *Journal of cognitive neuroscience*, *21*(8), 1536-1549.

Smith, J. C. (1976). Psychotherapeutic effects of transcendental meditation with controls for expectation of relief and daily sitting. *Journal of Consulting and Clinical Psychology*, *44*(4), 630.

Soriano-Ayala, E., Amutio, A., Franco, C., & Mañas, I. (2020). Promoting a Healthy Lifestyle through Mindfulness in University Students: A Randomized Controlled Trial. *Nutrients*, *12*(8). https://doi.org/10.3390/nu12082450

Stallman, H. M. (2010). Psychological distress in university students: A comparison with general population data [https://doi.org/10.1080/00050067.2010.482109]. *Australian Psychologist*, *45*(4), 249-257. https://doi.org/https://doi.org/10.1080/00050067.2010.482109

Stancák, J. A., Pfeffer, D., Hrudová, L., Sovka, P., & Dostálek, C. (1993). Electroencephalographic correlates of paced breathing. *Neuroreport*, *4*(6), 723-726.

Stephens, N. M., Townsend, S. S. M., Markus, H. R., & Phillips, L. T. (2012). A cultural mismatch: Independent cultural norms produce greater increases in cortisol and more negative emotions among first-generation college students. *Journal of Experimental Social Psychology*, *48*(6), 1389-1393. https://doi.org/10.1016/j.jesp.2012.07.008

Stewart, M., & Stavrianeas, S. (2008). Adapting the learning-cycle to enrich undergraduate neuroscience education for all students. *J Undergrad Neurosci Educ*, *6*(2), A74-77.

Struthers, C. W., Perry, R. P., & Menec, V. H. (2000). An Examination of the Relationship Among Academic Stress, Coping, Motivation, and Performance in College. *Research in Higher Education*, *41*(5), 581-592. https://doi.org/10.1023/A:1007094931292

Subramanya, P., & Telles, S. (2009). A review of the scientific studies on cyclic meditation. *International journal of yoga*, *2*(2), 46-48. https://doi.org/10.4103/0973-6131.60043

Sudsuang, R., Chentanez, V., & Veluvan, K. (1991). Effect of Buddhist meditation on serum cortisol and total protein levels, blood pressure, pulse rate, lung volume and reaction time. *Physiology & Behavior*, *50*(3), 543-548.

Swanbrow Becker, M., Roberts, S., Ritts, S., Branagan, W., Warner, A., & Clark, S. (2017). Supporting Transgender College Students: Implications for Clinical Intervention and Campus Prevention. *Journal of College Student Psychotherapy*, *31*, 1-22. https://doi.org/10.1080/87568225.2016.1253441

Takahashi, T., Murata, T., Hamada, T., Omori, M., Kosaka, H., Kikuchi, M., . . . Wada, Y. (2005). Changes in EEG and autonomic nervous activity during meditation and their association with personality traits. *International Journal of Psychophysiology*, *55*(2), 199-207.

Tang, Y.-Y., Ma, Y., Fan, Y., Feng, H., Wang, J., Feng, S., . . . Fan, M. (2009). Central and autonomic nervous system interaction is altered by short-term meditation. *Proceedings of the National Academy of Sciences*, *106*(22), 8865. https://doi.org/10.1073/pnas.0904031106

Tang, Y.-Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., . . . Fan, M. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings of the National Academy of Sciences*, *104*(43), 17152-17156.

Teper, R., & Inzlicht, M. (2012). Meditation, mindfulness and executive control: the importance of emotional acceptance and brain-based performance monitoring. *Social cognitive and affective neuroscience*, *8*(1), 85-92.

Teplan, M. (2002). Fundamentals of EEG measurement. *Measurement science review*, *2*(2), 1-11.

Thatcher, R. W. (2012). Coherence, Phase Differences, Phase Shift, and Phase Lock in EEG/ERP Analyses. *Developmental Neuropsychology*, *37*(6), 476-496. https://doi.org/10.1080/87565641.2011.619241

Tomljenović, H., Begić, D., & Maštrović, Z. (2016). Changes in trait brainwave power and coherence, state and trait anxiety after three-month transcendental meditation (TM) practice. *Psychiatr Danub*, *28*(1), 63-72.

Travis, F. (2001). Autonomic and EEG patterns distinguish transcending from other experiences during Transcendental Meditation practice. *International Journal of Psychophysiology*, *42*(1), 1-9. https://doi.org/https://doi.org/10.1016/S0167-8760(01)00143-X

Travis, F. (2011). Comparison of coherence, amplitude, and eLORETA patterns during Transcendental Meditation and TM-Sidhi practice. *Int J Psychophysiol*, *81*(3), 198-202. https://doi.org/10.1016/j.ijpsycho.2011.06.011

Travis, F., & Arenander, A. (2006). CROSS-SECTIONAL AND LONGITUDINAL STUDY OF EFFECTS OF TRANSCENDENTAL MEDITATION PRACTICE ON INTERHEMISPHERIC FRONTAL ASYMMETRY AND FRONTAL COHERENCE. *International journal of neuroscience*, *116*(12), 1519-1538. https://doi.org/10.1080/00207450600575482

Travis, F., Haaga, D. A. F., Hagelin, J., Tanner, M., Arenander, A., Nidich, S., . . . Schneider, R. H. (2010). A self-referential default brain state: patterns of coherence, power, and eLORETA sources during eyes-closed rest and Transcendental Meditation practice. *Cognitive Processing*, *11*(1), 21-30. https://doi.org/10.1007/s10339-009-0343-2

Travis, F., & Parim, N. (2017). Default mode network activation and Transcendental Meditation practice: Focused Attention or Automatic Self-transcending? *Brain and Cognition*, *111*, 86-94. https://doi.org/https://doi.org/10.1016/j.bandc.2016.08.009

Travis, F., Parim, N., & Shrivastava, A. (2017). Higher theta and alpha1 coherence when listening to Vedic recitation compared to coherence during Transcendental Meditation practice. *Consciousness and cognition*, *49*, 157-162.

Travis, F., & Shear, J. (2010). Focused attention, open monitoring and automatic self-transcending: Categories to organize meditations from Vedic, Buddhist and Chinese traditions. *Conscious Cogn*, *19*(4), 1110-1118. https://doi.org/10.1016/j.concog.2010.01.007

Travis, F., Tecce, J., Arenander, A., & Wallace, R. K. (2002). Patterns of EEG coherence, power, and contingent negative variation characterize the integration of transcendental and waking states. *Biological Psychology*, *61*(3), 293-319. https://doi.org/https://doi.org/10.1016/S0301-0511(02)00048-0

Travis, F., & Wallace, R. K. (1999). Autonomic and EEG patterns during eyes-closed rest and transcendental meditation (TM) practice: the basis for a neural model of TM practice. *Conscious Cogn*, *8*(3), 302-318. https://doi.org/10.1006/ccog.1999.0403

Tsai, J. F., Jou, S. H., Cho, W., & Lin, C. M. (2013). Electroencephalography when meditation advances: a case-based time-series analysis. *Cogn Process*, *14*(4), 371-376. https://doi.org/10.1007/s10339-013-0563-3

Valentine, E. R., & Sweet, P. L. (1999). Meditation and attention: A comparison of the effects of concentrative and mindfulness meditation on sustained attention. *Mental Health, Religion & Culture*, *2*(1), 59-70.

Versnik Nowak, A. L., DeGise, J., Daugherty, A., O'Keefe, R., Seward, S., Setty, S., & Tang, F. (2015). Prevalence and Predictors of Complementary and Alternative Medicine (CAM) Use Among Ivy League College Students: Implications for Student Health Services. *Journal of American College Health*, *63*(6), 362-372. https://doi.org/10.1080/07448481.2015.1042878

Wallace, R. K. (1970). Physiological effects of transcendental meditation. *Science*, *167*(3926), 1751-1754.

Wallace, R. K., & Benson, H. (1972). The physiology of meditation. *Scientific American*, *226*(2), 84-90.

Walton, K. G., Pugh, N. D., Gelderloos, P., & Macrae, P. (1995). Stress reduction and preventing hypertension: preliminary support for a psychoneuroendocrine mechanism. *The Journal of Alternative and Complementary Medicine*, *1*(3), 263-283.

Wei, M., Liao, K., Chao, R., Mallinckrodt, B., Tsai, P.-C., & Botello, R. (2010). Minority Stress, Perceived Bicultural Competence, and Depressive Symptoms Among Ethnic Minority College Students. *Journal of Counseling Psychology*, *57*, 411-422. https://doi.org/10.1037/a0020790

Wilkinson, R. T., & Houghton, D. (1982). Field test of arousal: a portable reaction timer with data storage. *Hum Factors*, *24*(4), 487-493. https://doi.org/10.1177/001872088202400409

Xie, L., Kang, H., Xu, Q., Chen, M. J., Liao, Y., Thiyagarajan, M., . . . Nedergaard, M. (2013). Sleep drives metabolite clearance from the adult brain. *Science (New York, N.Y.)*, *342*(6156), 373-377. https://doi.org/10.1126/science.1241224

Yoshida, K., Takeda, K., Kasai, T., Makinae, S., Murakami, Y., Hasegawa, A., & Sakai, S. (2020). Focused attention meditation training modifies neural activity and attention: longitudinal EEG data in non-meditators. *Social Cognitive and Affective Neuroscience*, *15*(2), 215-224. https://doi.org/10.1093/scan/nsaa020

Young, J. D., & Taylor, E. (1998). Meditation as a Voluntary Hypometabolic State of Biological Estivation. *News Physiol Sci*, *13*, 149-153. https://doi.org/10.1152/physiologyonline.1998.13.3.149

Zylowska, L., Ackerman, D. L., Yang, M. H., Futrell, J. L., Horton, N. L., Hale, T. S., . . . Smalley, S. L. (2008). Mindfulness meditation training in adults and adolescents with ADHD: a feasibility study. *Journal of Attention Disorders*, *11*(6), 737-746.

İnce, R., Adanır, S. S., & Sevmez, F. (2020). The inventor of electroencephalography (EEG): Hans Berger (1873–1941). *Child's Nervous System*. https://doi.org/10.1007/s00381-020-04564-z

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PUBLICATIONS

Lauren E. Guerriero, Shreyas Joshi, Josh Szydlik, and Bruce O’Hara (2020). The effectiveness of short meditation on attentional performance: A quick classroom activity of focused-breathing meditation. Manuscript submitted for publication.

Lauren E. Guerriero and Bruce F. O’Hara (2019). Meditation, sleep, and performance. *OBM Integrative and Complementary Medicine*, 4(2):18.

Chanung Wang, **Lauren E. Guerriero**, Trae C. Brooks, Asmaa A. Ajward, Sridhar Sunderam, Ashley W. Seifert, and Bruce F. O’Hara (2020). A comparative study of sleep and circadian rhythms between the house mouse (*Mus musculus*) and African spiny mouse (*Acomys cahirinus*). *Scientific Reports,* 10(1). doi:10.1038/s41598-020-67859-w