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BRIEF REPORT

Temporal and Spatial Characteristics of Meditation EEG

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Objective: This article discusses the importance of decisions made about the temporal and spatial characteristics of EEG during recording and analysis of meditation practices. ***Issue***: A recent meta-analysis averaged EEG in the alpha1 and alpha2 bands to characterize mindfulness practices. This ignored known differences in cognitive processing associated with these two bands, and so confounded their conclusion about brain patterns during mindfulness. Another paper averaged EEG from central electrodes, which reflect activity of motor cortices, and frontal electrodes, which reflect activity of the frontal association cortices, to characterize Transcendental Meditation practice. This averaged the signals from motor and frontal cortices, which respond to different behaviors, and so confounded any conclusion about the nature of brain patterns during Transcendental Meditation practice. Also, both of these papers reported power-derived measures. This misses the connectivity information that is captured in coherence analysis. ***Conclusion:*** Meditation researchers should (a) investigate narrow frequency bands, especially theta1, theta2, alpha1 and alpha2, which are known to reflect different cognitive processes, (b) average EEG over theoretically known spatial areas, and (c) employ power as well as coherence analysis to more accurately define different categories of meditation practices and more reliably apply meditation practices to specific subject populations.

Clinical Impact Statement
Three recommendations emerge from this paper. First, investigate narrow frequency bands that reflect discrete cognitive processes. Second, choose sensors to average that are theoretically tied to specific cognitive activities. Third, choose a measure of the brain's connectome that gives a picture of network dynamics.

Keywords: meditation, EEG, power, coherence, alpha1

Meditation practices have brought new categories of experience into the realm of scientific investigation such as insight—solving a problem by intuition rather than by systematic critical reasoning (Lutz, Slagter, Dunne, & Davidson, 2008), or the experience of pure consciousness—a completely peaceful mental state in which the mind is awake, but still (Travis & Pearson, 2000). To understand the brain dynamics of these new categories of experience, researchers need to investigate narrow frequency bands, especially theta1, theta2, alpha1 and alpha2, which are known to reflect different cognitive processes, average EEG over theoretically known spatial areas, and consider the utility of coherence analysis to capture EEG connectivity patterns.

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Temporal and Spatial Information in EEG Recordings

EEG provides millisecond resolution to identify patterns of brain activation during tasks (Hinault, Larcher, Zazubovits, Gotman, & Dagher, 2019). Brain activation patterns are reflected in EEG coherence, a measure of variability of phase between the raw EEG time series recorded from pairs of electrodes (Thatcher, Walker, & Giudice, 1987). High coherence between two electrodes indicates that the brain areas under those sensors are part of a larger network of brain connections, called the connectome, which underlie information processing (8–20 Hz) (Fries, 2015; Atasoy, Donnelly, & Pearson, 2016). There is important temporal and spatial information in the EEG.

Temporal Information in EEG Recordings

Gamma EEG

Activity in the gamma band (30–50 Hz) reflects local processing within short-range connections responsible for object recognition and the construction of content of experience (Lubar, 1997; Singer, 1999). Gamma band activity correlates with increased blood flow in brain areas involved in task processing. Gamma band is reported in meditation practices that require concentration and control of the mind, such as Vipassana or Compassion meditation (Lutz et al., 2008).

Alpha2 EEG (10–12 Hz)

Activity in the "alpha" band has been considered a sign of cortical idling (Pfurtscheller, Stancák, & Neuper, 1996). This characteristic of "idling" is true for the alpha2 band—10 to 12 Hz. In eyes closed conditions, alpha2 power in posterior areas is associated with decreased blood and is thought to play a role in perceptual tuning of sensory areas in anticipation of visual events by deactivating brain areas involved in irrelevant processing (Ergenoglu et al., 2004). In resting conditions when the body is relaxing, alpha2 power is seen in central leads, which are over the motor system (Kornhuber & Deecke, 1965; Rimbert, Al-Chwa, Zaepffel, & Bougrain, 2018). Alpha2 activity is reported in many mindfulness practices (Ahani et al., 2014; Dunn, Hartigan, & Mikulas, 1999; Hinterberger, Schmidt, Kamei, & Walach, 2014; Lagopoulos et al., 2009).

Alpha1 EEG (8–10 Hz)

The classical understanding of "alpha" as cortical idling holds for EEG in the alpha2 band during simple *sensorimotor* tasks. In contrast, alpha1 activity (8 – 10 Hz) in association cortices *positively* covaries with task demands and is associated with higher blood flow (Mahone, Travis, Gevirtz, & Hubbard, 2018). This so-called "paradoxical" frontal alpha1 is reported during tasks involving internally directed attention (Shaw, 1996) such as imagining a tune compared to listening to the same tune (Cooper, Burgess, Croft, & Gruzelier, 2006). Alpha1 activity in association areas may represent liveliness of the "screen of consciousness," which provides a context for grouping isolated elements into the unity of experience (Sadaghiani & Kleinschmidt, 2016). For instance, when solving a problem by intuition or insight, there is a burst of alpha1 activity followed by a burst in the gamma band when the idea comes to mind (Kounios & Beeman, 2009). Alpha1 activity is reported during Transcendental Meditation practice and in studies of a Qigong master and of Zen-Buddhist priests in Taiwan (Huang & Lo, 2009; Qin, Jin, Lin, & Hermanowicz, 2009; Travis et al., 2010).

EEG in Alpha1 and Alpha2 Bands in Meditation Research

A recent meta-analysis of EEG patterns during mindfulness meditations did not attend to the differences between the alpha1 and alpha2 bands in characterizing brain patterns during mindfulness practices. This paper concluded that mindfulness practices are characterized by theta and "alpha" EEG patterns (Lomas, Ivtzan, & Fu, 2015). One study in this meta-analysis did report increased frontal alpha-1 power. This study investigated Zen Buddhist priests reporting "transcendence" and "inner radiance" (Huang & Lo, 2009). See (Travis & Shear, 2010) for a discussion why alpha1 might be seen in very experienced meditation practitioners. The other eight studies in the meta-analysis reported increased "alpha" power in *parietal* and *central* areas, which as discussed above, are examples of alpha2 EEG. Thus, this meta-analysis could more accurately conclude that mindfulness practices are characterized by theta and *alpha2* EEG patterns.

Attending to differences in alpha1 and alpha2 EEG is critical for building a clearer picture of brain patterns underlying different meditation practices. Meditations in the *Automatic Self-Transcending* category are characterized by frontal alpha1 EEG (Travis & Shear, 2010). This pattern is different in spatial location (frontal rather than parietal and occipital) and frequency (alpha1 rather than alpha 2) from meditations in the Open Monitoring category (Travis & Shear, 2010), which includes mindfulness practices.

Spatial Information in EEG Recordings

A well-known limitation of EEG analysis is poor spatial resolution. The electrical activity recorded at a specific sensor includes contributions from brain activity near to the sensor as well as volume conductance from all other brain areas (Barzegaran & Knyazeva, 2017; von Ellenrieder, Dan, Frauscher, & Gotman, 2016). Despite this smearing of brain signals, EEG patterns over larger cortical areas reflect activity of those cortical areas. For instance, EEG recorded at occipital sensors index visual processing (Zumer, Scheeringa, Schoffelen, Norris, & Jensen, 2014). EEG recorded at central sensors reflect activation and deactivation of the motor cortex (Kajihara et al., 2015). EEG recorded at frontal sensors reflects levels of reinforcement learning, decision making and monitoring response conflict (Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003; van de Vijver, Cohen, & Ridderinkhof, 2014).

Choice of Spatial Locations in Meditation Research

Random assignment, controlled longitudinal and cross-sectional studies report that Transcendental Meditation practice is characterized by increases in prefrontal coherence measured among F3, Fz, F4, AF3, AF4, F5, F6, and AFz (Travis et al., 2010; Travis & Wallace, 1999; Travis, Tecce, Arenander, & Wallace, 2002). The involvement of prefrontal areas with Transcendental Meditation practice is supported by a recent blood flow study that reported increases in the anterior cingulate gyrus and dorsolateral prefrontal cortex during Transcendental Meditation practice (Mahone et al., 2018). The importance of frontal brain activity during Transcendental Meditation practice is also supported by a MEG study reporting magnetic field potentials in the medial prefrontal and anterior cingulate cortices during Transcendental Meditation practice (Yamamoto, Kitamura, Yamada, Nakashima, & Kuroda, 2006).

A recent single-group design of Transcendental Meditation practice averaged EEG from sensors over fronto-central, centro-parietal, and bilateral temporal areas to compare patterns before learning Transcendental Meditation during eyes-closed rest and after learning the practice (Kang et al., 2018). In this study, the fronto-central areas included three frontal sensors (F1, Fz, F2) and six sensors over the premotor and motor cortices (FC1, FCz, FC2, C1, Cz, and C2).

Averaging EEG over frontal and central sensors could have confounded the findings from Kang's study. Alpha over the motor cortices would reflect cortical inhibition and be in the alpha2 band. Alpha2 activity over motor cortices would be similar during simple eyes-closed rest and meditation since both involve the body relaxing when sitting easily. Since 2/3 of the sensors in the fronto-central average were over premotor and motor circuits, the "alpha" values reported in this study included major contributions from alpha2 in the motor system and minor contributions from alpha1 in frontal areas. This confounded the conclusions from this study. If the lab had averaged sensors in prefrontal areas, such as F1, F3, Fz, F2, F4, F5, F6, AF3, AF4, and AFz, then their findings would better compare to other EEG studies of Transcendental Meditation practice.

Power and Coherence Analysis of EEG

Power and coherence analysis give two different pictures of brain dynamics. Power reflects short-range coherence in the millimeter range under the sensor; coherence reflects stability in phase relationships between spatially distributed sensors (long range coherence) (Thatcher, 2012).

Coherence and Cognitive Development From Infancy to Adulthood

Investigating changes in brain connectivity across childhood, Thatcher and colleagues found that coherence was more sensitive than power to changes in brain circuits over childhood (Thatcher et al., 1987). Patterns of long-distance coherence between the prefrontal cortex, the executive system, and the back of the brain, the data driven system, increase systematically during childhood (Knyazev et al., 2017). With increasing long-range connections, cognitive abilities transform from concrete operations, thinking about objects, to formal operations, "thinking about thinking" or critical thinking (Travis, 2016). In addition, throughout childhood connections within the default mode network (DMN) grow richer, while connections between the DMN and the central executive network (CEN) decrease. This marks the segregation of inner orientation (DMN) from processing of outer stimuli (CEN), which is a prerequisite for attentional and behavioral control (Knyazev et al., 2017).

Power and Coherence in Meditation Populations

Higher alpha1 power has been reported during Transcendental Meditation in one study (Travis et al., 2010) but not others (Dillbeck & Bronson, 1981; Travis & Wallace, 1999). The vast majority of studies report higher coherence during Transcendental Meditation practice specifically in the alpha1 band and between frontal sensors (Travis et al., 2010; Travis & Wallace, 1999; Travis et al., 2002). The alpha band frequency reflects long range brain connections underlying attention and consciousness (Palva & Palva, 2007) and the movement of attention from outer focus to inner focus, independent of visual stimuli (Ben-Simon et al., 2013). The known relation of attention and EEG in the alpha band fits the description of transcending during Transcendental Meditation practice—the shifting of attention from changing thoughts and feelings to a perfectly peaceful mental state in which the mind is awake, but still, as reported during Transcendental Meditation practice (Travis & Parim, 2017; Travis & Pearson, 2000).

A meta-analysis of mindfulness practices reported patterns of power during these practices, but not coherence (Lomas et al., 2015). This meta-analysis reported significantly higher theta power in 10 studies, reductions in theta activity in three studies and no differences in six others. This study also reported significantly higher alpha power in 13 studies, reductions in alpha in one study, and no difference in six others. Differences were less robust in the beta band: four studies reported significantly higher beta during mindfulness practices, one reported decreases and seven others reported no differences. Coherence during mindfulness and also EEG activity in the alpha1 and alpha2 frequency bands, as discussed earlier, would better describe brain patterns during mindfulness practices.

Power and Coherence in Clinical Populations

Coherence patterns distinguish clinical populations from normal controls better than power values (Thatcher et al., 2001). Subjects suffering from traumatic brain injury exhibit significant decreases in long-distance connectivity and significant increase in short-distance connectivity or "small-world network" connections (Cao & Slobounov, 2010). Small-world networks define regional specialization in contrast to long range connections—the output from different areas are not being integrated into a larger whole (Telesford, Joyce, Hayasaka, Burdette, & Laurienti, 2011).

Subjects diagnosed with Alzheimer dementia or mild cognitive impairment exhibit impairment in long range cortical networks. Specifically, connectivity between frontal executive centers and the parietal and temporal processing areas is compromised (Babiloni et al., 2016) with the greatest decreases in coherence seen in theta and alpha bands (Adler, Brassen, & Jajcevic, 2003; Wang, Wang, Yu, Wei, Yang, & Deng, 2016).

A cluster of disorders including Attention Deficit Hyperactive Disorder (ADHD), schizophrenia and Obsessive Compulsive Disorder were characterized by power increases in lower frequencies (delta and theta) and decreases across higher frequencies (alpha, beta and gamma) (Newson & Thiagarajan, 2019). Similar patterns have been reported for coherence—delta coherence was higher and alpha1 coherence was lower in subjects diagnosed with schizophrenia (Lehmann et al., 2014). Activity in the delta band is associated with inhibition of cortical areas that would lead to interrupted mental processing.

Impact of Higher Frontal Alpha Coherence on Trauma

Higher frontal alpha coherence during Transcendental Meditation practice leads to higher coherence after the meditation session. After three months TM practice, frontal alpha coherence was significantly higher during computer tasks in college students (Travis et al., 2009) and school administrators (Travis et al., 2018), and stress reactivity was significantly lower. In 10- to 14-year-olds, ADHD symptoms as measured by theta/beta ratios significantly decreased after three months TM practice and continued to decrease after 6-months practice (Travis, Grosswald, & Stixrud, 2011). EEG coherence also increased in alpha and beta frequencies supporting reductions in ADHD symptoms in these subjects. PTSD symptoms also are reported to significantly decrease with Transcendental Meditation practice in Vietnam Veterans compared to usual psychological therapy (Brooks & Scarano, 1985), Iraqi vets compared to themselves (Kang et al., 2018) and compared to Prolonged Exposure (Nidich et al., 2018), and in African refugees compared to matched controls (Rees, Travis, Shapiro, & Chant, 2013, 2014).

Conclusion

Three recommendations emerge from this discussion to help guide future meditation research. First, researchers should investigate narrow frequency bands, especially theta1, theta2, alpha1 and alpha2. These bands, while being close in frequency, reflect quite different cognitive processes—drowsiness is associated with theta1 while inner memory processes are associated with theta 2; inner wakefulness is associated with alpha1 while idling is associated with alpha2. Second, the choice of sensors to average should take into consideration the types of cognitive activities associated with different brain areas. While there is significant smearing of scalp recorded EEG, there are major contributions from brain areas under the sensor as well. Last, with the new understanding of connectome of the brain, coherence analysis should be conducted as well as power-related analyses. These considerations could help research more accurately different categories of meditation practices and more reliably apply meditation practices to specific subject populations.

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