Available online at www.sciencedirect.com
ScienceDirect
Current Opinion in Psychology

Frontal theta activity and white matter plasticity following mindfulness meditation

Yi-Yuan Tang[1], Rongxiang Tang[2], Mary K Rothbart[3] and Michael I Posner[3]

Both brain alpha and theta power have been examined in the mindfulness meditation literature and suggested as key biological signatures that potentially facilitate a successful meditative state. However, the exact role of how alpha and theta waves contribute to the initiation and maintenance of a meditative state remains elusive. In this perspective paper, we discuss the role of frontal midline theta (FMθ) activity in brain white matter plasticity following mindfulness meditation. In accordance with the previous studies in humans, we propose that FMθ activity indexes the control needed to maintain the meditation state; whereas alpha activity is related to the preparation needed to achieve the meditative state. Without enough mental preparation, one often struggles with and has difficulty achieving a meditative state. Animal work provides further evidence supporting the hypothesis that mindfulness meditation induces white matter changes through increasing FMθ activity. These studies shed light on how to effectively enhance brain plasticity through mindfulness meditation.

Addresses
[1] Department of Psychological Sciences, Texas Tech University, Lubbock, TX, USA
[2] Department of Psychological and Brain Sciences, Washington University in St. Louis, St. Louis, MO, USA
[3] Department of Psychology, University of Oregon, Eugene, OR, USA

Current Opinion in Psychology 2019, **28**:294–297

This review comes from a themed issue on **Mindfulness**

Edited by **Amit Bernstein**, **David Vago** and **Thorsten Barnhofer**

https://doi.org/10.1016/j.copsyc.2019.04.004

2352-250X/© 2018 Elsevier Inc. All rights reserved.

Introduction

Mindfulness meditation has been shown to induce positive changes at both behavioral and neural levels [1•]. A short-term mindfulness meditation, integrative body-mind training (IBMT), can improve positive moods, reduce negative moods, decrease levels of the stress hormone cortisol, and increase anterior cingulate cortex (ACC) activity [2,3]. Our studies using electroencephalogram (EEG) showed increased theta activity in frontal midline (FMθ) electrodes even during the resting-state following meditation training [3]. This finding was consistent with other meditation studies [4•,5–7]. Longer mindfulness training, such as 2–4 weeks of IBMT, induced changes in white matter pathways surrounding the ACC as measured by increased fractional anisotropy using diffusion tensor imaging [8,9]. The time course of such changes began with white matter change in axonal density after two weeks of training, followed by changes in both myelination and axonal density after four weeks of training [9].

Mindfulness meditation is a systematic training of attention and self-control capacities, thus requiring the active engagement of ACC [1•,2,10,11]. Meditators during the resting state were found to exhibit increased brain metabolism in the ACC [12], and another study found that FMθ activity is positively correlated with glucose metabolism in the ACC [13]. In this paper, we hypothesize that FMθ activity may increase proliferation of active oligodendrocytes, leading to increased myelination, thereby improving structural connectivity between the ACC and limbic areas [14,15].

Theta and alpha activity following meditation

Beta brainwaves (15–40 Hz) are often associated with thinking and high arousal. Compared to beta, alpha waves (9–14 Hz) are slower and higher in amplitude and represent a low arousal, restful and relaxed state. Theta waves (5–8 Hz) have even slower frequency and greater amplitude and compared to alpha [16]. Typically, a meditator needs to initiate and maintain a relaxed and/or calm state before entering a deeper meditative state. This change in state often necessitates switching from beta activity to alpha activity and subsequently to theta activity. However, EEG effects of mindfulness meditation have shown mixed results, sometimes showing increases, decreases, or even no differences across all bandwidths when compared to resting state and task state studies [4•,5–7,17–19].

A recent systematic review including 56 papers with a total 1715 subjects (1358 healthy individuals and 357 psychiatric patients) found that mindfulness meditation was most commonly associated with enhanced alpha and theta power as compared to an eyes closed resting state. However, no consistent patterns were observed in beta, delta and gamma bandwidths [4•]. These results are in line with our series of IBMT studies demonstrating increased theta (and some alpha) activity in ACC and adjacent prefrontal cortex (PFC) and better performance on tasks of attention, working memory, creativity and problem solving [1•,2,10,20–22].

An earlier systematic review also indicated that meditation induces brain changes in the ACC and PFC and that theta and alpha activities are related to proficiency of practice [23]. This finding supports the hypothesis that mindfulness meditation is associated with increased alpha and theta power in both healthy and patient populations. Yet different types of meditation practices or techniques may involve or emphasize different components and may elicit different brainwaves [4•,10,23,24,25•].

In addition to the wide range of mindfulness techniques, different stages of the same practice may also contribute to differences in behavior, physiology and brain activity [1•,3,10,24]. We proposed three stages of meditation practice that are related to different brainwaves and brain changes [1•,24,26–29]. The early and middle stages involve effortful control with more beta and alpha activity, whereas the advanced stage engages more effortless control and thus more theta and alpha activity [1•,10]. The early stage of meditation often involves lateral PFC and parietal areas [24,25•,26–29]. During the middle stage, people begin to exert an appropriate effort to minimize distractions and mind wandering. Distraction involves diverse brain networks such as frontal, parietal, temporal cortex and limbic areas depending on the strategies used [1•,26–28]. In the advanced stage, little or no effort is needed; instead the meditative state is maintained by activity in the ACC, striatum and insula, accompanied by high parasympathetic activity and reduced activity in the lateral PFC and parietal areas [1•,10].

Considering the model of successive stages mentioned above [26–29], we propose that alpha activity serves as a biomarker of a state change from mind wandering to a relaxed and calm mental state during the preparation for meditation. Theta power serves as a biomarker of meditative state itself and is associated with brain changes. Consistent with the literature, FMθ activity and somatosensory alpha rhythms are often observed during executive functions, cognitive control and the active monitoring of sensory information [10,30,31]. Increased FMθ activity is also detected during meditation compared to mind wandering [4•,5–7]. In a study examining different meditative states, increased FMθ activity (and decreased beta and low gamma) indexes a deeper meditative state, while alpha activity is increased in all meditative states, suggesting that it is not depth-related [7].

Network and cellular mechanisms of white matter changes

The ACC is part of an executive network that is involved in the control of feelings and thoughts.

In addition to the ACC, the executive network involves the anterior insula and underlying striatum [32•]. Our meditation studies found improved connectivity in pathways surrounding the ACC following mindfulness meditation [8,9]. Moreover, other studies of mice have indicated that both low frequency stimulation and motor learning can activate oligodendrocytes and thus change connectivity [33,34]. We hypothesized [14] that theta range stimulation can serve to increase the number of active oligodendrocytes ready to support myelination. An increase in myelination would reduce the g ratio (axon size divided by axon size + myelin), thus supporting behavioral change by increasing the speed and accuracy of connections between brain areas [35].

To examine the cellular mechanisms of white matter changes, we conducted mouse studies [36,37]. We implanted lasers in the ACC of genetically altered mice to increase or decrease spiking of output neurons when stimulated by laser light at 1, 8 or 40 Hz in comparison with a non-stimulation control. We found that increased spiking of ACC neurons during low-frequency stimulation (1 and 8 Hz) produced an increase in the cells capable of increasing myelin (oligodendrocytes). Higher frequency stimulation or rhythmic decreases in output firing were not effective in activating dormant oligodendrocytes. The increase in active oligodendrocytes resulted in the hypothesized reduced g ratio as measured by electron microscopy in the corpus callosum near the site of stimulation but not in control sites remote from stimulation.

We also found a behavioral change in mice whose output had been increased by low frequency stimulation. Mice stimulated with 1 and 8 Hz increased time spent in the light in a light/dark box paradigm [37]. This suggested that these mice had decreased anxiety, conceptually similar to what is observed following meditation training in humans [1•,2].

Since 1 Hz resulted in the largest increases in myelinating cells and 8 Hz produce the largest behavioral change we do not know the optimal stimulation. It could be that the optimal stimulation lies between 1 and 8 Hz (within the theta range for mice), or it could be that the best rhythm for stimulating cells is different than the optimal rhythm for changing behavior. However, our results show that low-frequency stimulation can result in activity-dependent remodeling of myelination, giving rise to enhanced connectivity and altered behavior. These studies demonstrated the role of low frequency (near theta) stimulation in altering white matter, thus supporting our hypothesis on how meditation changes white matter [36,37].

Conclusions

This paper summarizes human and animal studies that demonstrate increased FMθ activity is associated with brain white matter plasticity, suggesting that this could be the mechanism for changes in white matter following mindfulness meditation. Based on animal studies, the underlying cellular mechanisms involves increased oligodendrocyte proliferation which results in lowered g ratio and an increase in myelination. These results shed lights on how meditation may induce brain white matter changes through increased FMθ activity. We believe that improved plasticity through mindfulness meditation, depends on eliciting deeper meditative states with lower frequency and greater amplitude EEG during and following training.

As a field, we are at an exciting and critical stage for elucidating the precise mechanisms of action through which mindfulness training and practices induce their benefits on brain, physiology and behavior. Finding appropriate, theory-driven and empirically supported indexes and biomarkers would greatly improve our likelihood of success and make meaningful contribution to the field of mindfulness.

According to our lines of work focusing on self-control networks involving the ACC and brain plasticity in white matter surrounding this key region following mindfulness meditation, we propose that FMθ activity could play an important role. For future scientific and clinical endeavors that seek to specifically strengthen and enhance brain plasticity through mindfulness meditation, FMθ activity may be an appropriate index at the initial stage of training, especially during training, for monitoring and providing useful feedback to participants with regard to their practice and depth of meditative states. Deficits in self-control and activation of the ACC have been associated with many disorders such as ADHD, addiction, autism, mood disorders, dementia, schizophrenia, and others. Given that FMθ activity is also positively correlated with glucose metabolism in the ACC and increased FMθ activity is associated with brain white matter plasticity related to self-control networks such as the ACC, FMθ activity may further serve as an important biomarker for treatment of mental disorders and one of the critical steps in the neurophysiological cascade of brain plasticity. Using it as a putative mechanistic target for understanding brain plasticity and its associated behavioral changes would be useful not only for mindfulness research, but also for investigations that go beyond our field of study.

Conflict of interest statement

Nothing declared.

Acknowledgements

This research was supported by ONRN00014-17-2824 and N00014-15-2148 and N.I.H.R61AT010138.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest

1. Tang YY, Holzel BK, Posner MI: **The neuroscience of mindfulness meditation**. *Nat Rev Neurosci* 2015, **16**:213-225.
•
A comprehensive and systematic review of the brain mechanisms following mindfulness meditation.

2. Tang YY, Ma Y, Wang J, Fan Y, Feng S, Lu Q, Yu Q, Sui D, Rothbart MK, Fan M, Posner MI: **Short term meditation training improves attention and self-regulation**. *Proc Natl Acad Sci U S A* 2007, **104**:17152-17156.

3. Tang YY, Ma Y, Fan Y, Feng H, Wang J, Feng S *et al.*: **Central and autonomic nervous system interaction is altered by short-term meditation**. *Proc Natl Acad Sci U S A* 2009, **106**:8865-8870.

4. Lomas T, Ivtzan I, Fu CH: **A systematic review of the neurophysiology of mindfulness on EEG oscillations**. *Neurosci Biobehav Rev* 2015, **57**:401-410.
•
A comprehensive and systematic review of the neurophysiology of mindfulness meditation.

5. Brandmeyer T, Delorme A: **Reduced mind wandering in experienced meditators and associated EEG correlates**. *Exp Brain Res* 2018, **236**:2519-2528.

6. Wong WP, Camfield DA, Woods W, Sarris J, Pipingas A: **Spectral power and functional connectivity changes during mindfulness meditation with eyes open: a magnetoencephalography (MEG) study in long-term meditators**. *Int J Psychophysiol* 2015, **98**:95-111.

7. DeLosAngeles D, Williams G, Burston J, Fitzgibbon SP, Lewis TW, Grummett TS, Clark CR, Pope KJ, Willoughby JO: **Electroencephalographic correlates of states of concentrative meditation**. *Int J Psychophysiol* 2016, **110**:27-39.

8. Tang YY, Lu Q, Geng X, Stein EA, Yang Y, Posner MI: **Short-term meditation induces white matter changes in the anterior cingulate**. *Proc Natl Acad Sci U S A* 2010, **107**:15649-15652.

9. Tang YY, Lu Q, Fan M, Yang Y, Posner MI: **Mechanisms of white matter changes induced by meditation**. *Proc Natl Acad Sci U S A* 2012, **109**:10570-10574.

10. Tang YY: *The Neuroscience of Mindfulness Meditation: How the Body and Mind Work Together to Change Our Behavior?* Springer Nature; 2017.

11. Cavanagh JF, Frank MJ: **Frontal theta as a mechanism for cognitive control**. *Trends Cogn Sci* 2014, **18**:414-421.

12. Lou HC, Kjaer TW, Friberg L, Wildschiodtz G, Holm S, Nowak M: **A 15O-H2O PET study of meditation and the resting state of normal consciousness**. *Hum Brain Mapp* 1999, **7**:98-105.

13. Pizzagalli DA, Oakes TR, Davidson RJ: **Coupling of theta activity and glucose metabolism in the human rostral anterior cingulate cortex: an EEG/PET study of normal and depressed subjects**. *Psychophysiology* 2003, **40**:939-949.

14. Posner MI, Tang YY, Lynch G: **Mechanisms of white matter change induced by meditation training**. *Front Psychol* 2014, **5**:1220.

15. Posner MI: **Rehabilitating the brain through meditation and electrical stimulation**. *Cortex* 2018. [Epub ahead of print].

16. Başar E, Güntekin B: **Review of delta, theta, alpha, beta, and gamma response oscillations in neuropsychiatric disorders**. *Suppl Clin Neurophysiol* 2013, **62**:303-341.

17. Jevning R, Wallace RK, Beidebach M: **The physiology of meditation: a review. A wakeful hypometabolic integrated response**. *Neurosci Biobehav Rev* 1992, **16**:415-424.

18. Travis F, Shear J: **Focused attention, open monitoring and automatic self-transcending: categories to organize meditations from Vedic, Buddhist and Chinese traditions**. *Conscious Cogn* 2010, **19**:1110-1118.

19. Chiesa A: **Zen meditation: an integration of current evidence**. *J Altern Complement Med* 2009, **15**:585-592.

20. Fan Y, Tang YY, Tang R, Posner MI: **Time course of conflict processing modulated by brief meditation training**. *Front Psychol* 2015, **6**:911.

21. Fan Y, Tang YY, Tang R, Posner MI: **Short term integrative meditation improves resting alpha activity and stroop performance**. *Appl Psychophysiol Biofeedback* 2014, **39**:213-217.

22. Xue SW, Tang YY, Tang R, Posner MI: **Short-term meditation induces changes in brain resting EEG theta networks**. *Brain Cogn* 2014, **87**:1-6.

23. Cahn BR, Polich J: **Meditation states and traits: EEG, ERP, and neuroimaging studies**. *Psychol Bull* 2006, **132**:180-211.

24. Tang YY, Posner MI: **Theory and method in mindfulness neuroscience**. *Soc Cogn Affect Neurosci* 2013, **8**:118-120.

25. • Lutz A, Slagter HA, Dunne JD, Davidson RJ: **Attention regulation and monitoring in meditation**. *Trends Cogn Sci* 2008, **12**:163-169.
This paper demonstrates the two types of meditation — focus based and open-monitoring based.

26. Tang YY, Posner MI: **Attention training and attention state training**. *Trends Cogn Sci* 2009, **13**:222-227.

27. Tang YY, Rothbart MK, Posner MI: **Neural correlates of establishing, maintaining, and switching brain states**. *Trends Cogn Sci* 2012, **16**:330-337.

28. Tang YY, Posner MI: **Training brain networks and states**. *Trends Cogn Sci* 2014, **18**:345-350.

29. Tang YY, Posner MI, Rothbart MK, Volkow ND: **Circuitry of self-control and its role in reducing addiction**. *Trends Cogn Sci* 2015, **19**:439-444.

30. Cohen MX: **A neural microcircuit for cognitive conflict detection and signaling**. *Trends Neurosci* 2014, **37**:480-490.

31. Jo HG, Malinowski P, Schmidt S: **Frontal theta dynamics during response conflict in long-term mindfulness meditators**. *Front Hum Neurosci* 2017, **11**:299.

32. • Petersen SE, Posner MI: **The attention system of the human brain: 20 years after**. *Annu Rev Neurosci* 2012, **35**:73-89.
A comprehensive review of attention system of human brain.

33. Gibson EM, Purger D, Mount CW, Goldstein AK, Lin GL, Wood LS, Inema I, Miller SE, Bieri G, Zuchero JB *et al.*: **Neuronal activity promotes oligodendrogenesis and adaptive myelination in the mammalian brain**. *Science* 2014, **344**:1252304.

34. McKenziee IA, Ohayon D, Li H, de Faria JP, Emery B, Tohyama K, Richardson WD: **Motor skill learning requires active central myelination**. *Science* 2014, **346**:318-322.

35. Fields RD: **A new mechanism of nervous system plasticity: activity-dependent myelination**. *Nat Rev Neurosci* 2015, **16**:756-767.

36. Piscopo DM, Weible AP, Rothbart MK, Posner MI, Niell CM: **Changes in white matter in mice resulting from low-frequency brain stimulation**. *Proc Natl Acad Sci U S A* 2018, **115**:E6339-E6346.

37. Weible AP, Piscopo DM, Rothbart MK, Posner MI, Niell CM: **Rhythmic brain stimulation reduces anxiety-related behavior in a mouse model based on meditation training**. *Proc Natl Acad Sci U S A* 2017, **114**:2532-2537.