Short-term meditation induces changes in brain resting EEG theta networks

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ABSTRACT

Many studies have reported meditation training has beneficial effects on brain structure and function. However, very little is known about meditation-induced changes in brain complex networks. We used network analysis of electroencephalography theta activity data at rest before and after 1-week of integrative body–mind training (IBMT) and relaxation training. The results demonstrated the IBMT group (but not the relaxation group) exhibited significantly smaller average path length and larger clustering coefficient of the entire network and two midline electrode nodes (Fz and Pz) after training, indicating enhanced capacity of local specialization and global information integration in the brain. The findings provide the evidence for meditation-induced network plasticity and suggest that IBMT might be helpful for alterations in brain networks.

1. Introduction

Meditation can be conceptualized as a family of complex emotional and attentional regulatory training regimes (Lutz, Slagter, Dunne, & Davidson, 2008). In research and clinical contexts, mindfulness meditation is often defined as a practice with nonjudgmental attention to experiences in the present moment (Kabat-Zinn, 1990). However, one of the major issues in the literature is the inconsistency of operational definitions of meditation (Awasthi, 2013; Cahn & Polich, 2006; Williams & Kabat-Zinn, 2011). For example, Bishop et al. (2004) proposed an operational definition including self-regulation of attention, which would seem to be one of the key ingredients believed to be active in mindfulness. Nevertheless, mindfulness neuroscience or contemplative neuroscience is an emerging research field that investigates the underlying mechanisms of different mindfulness practices, different stages and different states of practice as well as different effects of practice over the lifespan. Mindfulness neuroscience research integrates theory and methods from eastern contemplative traditions, western psychology and neuroscience, and from neuroimaging techniques, physiological measures and behavioral tests (Tang & Posner, 2013).

Meditation has recently received increasing attention as a vehicle for understanding training-related brain plasticity. Previous studies have reported meditation relates to changes in brain structure and function such as increased regional cortical thickness (Lazar et al., 2005), grey matter densities (Luders, Toga, Lepore, & Gaser, 2009; Vestergaard-Poulsen et al., 2009), white matter connectivity (Luders, Clark, Narr, & Toga, 2011; Tang, Lu, Fan, Yang, & Posner, 2012; Tang et al., 2010), reorganization of cognitive resources (Hölzel et al., 2011; Slagter et al., 2007), and the default mode network connectivity (Brewer et al., 2011; Jang et al., 2011).

Integrative Body–Mind Training (IBMT) is one form of mindfulness meditation that originates from ancient eastern contemplative traditions, including traditional Chinese medicine, Zen, etc. IBMT shares several key components with other forms of meditation, including relaxation, mental imagery, and mindfulness. IBMT stresses no effort or less effort to control thoughts, and the achievement of a state of restful alertness that allows a high degree of awareness and balance of the body, mind, and environment (Tang, Rothbart, & Posner, 2012). A number of randomized clinical trials indicate that IBMT improves attention and self-regulation and induces neuroplasticity through interaction between the central and the autonomic nervous systems (Tang et al., 2007; Tang et al., 2009; Tang et al., 2010). For example, 4-week IBMT has been

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reported to increase network efficiency of the anterior cingulate cortex (Xue, Tang, & Posner, 2011) and connectivity of the white matter surrounding the anterior cingulate cortex (Tang et al., 2010; Tang et al., 2012).

Recently, brain networks derived from functional magnetic resonance imaging (fMRI) or electroencephalography (EEG) have been consistently reported to exhibit an optimal organization pattern for information processing, such as high clustering coefficient and short path lengths (Stam, Jones, Nolte, Breakspear, & Scheltens, 2007), and high efficiency of information transfer for low wiring costs (Achard & Bullmore, 2007), suggesting the balance of functional integration and segregation (Rubinov & Sporns, 2010). Recent studies indicated differences in the network topological parameters associated with an array of factors including diseases (Seeley, Crawford, Zhou, Miller, & Greicius, 2009) and different task conditions (Bullmore & Sporns, 2009). Besides, using network science to evaluate exercise-associated brain changes is also becoming increasingly attractive (Bassett et al., 2011; Burdette et al., 2010).

Electrophysiological studies have observed altered theta activity is linked to meditation practice (Cahn & Polich, 2006; Rubia, 2009; Tang et al., 2009). Our previous study has also reported five days of IBMT induced increased EEG power in the theta frequency band at frontal midline electrodes (Tang et al., 2009). Based on these studies, we hypothesize that meditation experience is associated with changes in brain networks derived from resting-state EEG theta activity. We thus combine synchronization likelihood method, network analysis, and IBMT to test the hypothesis.

2. Methods

2.1. Participants

Forty-five healthy Chinese students (29 males, mean age, 22.9 ± 1.55 (SD) yrs, all right-handed) without any previous meditation or relaxation training experience were recruited through advertisements in Dalian University of Technology, and randomly assigned to an experimental group (IBMT, 24 subjects, mean age 22.9 ± 1.6 yrs) and a relaxation training control group (21 subjects, mean age 22.8 ± 1.5 yrs). They all provided their written informed consent. The experiment was approved by the local Institutional Review Board.

2.2. Training

Twenty-four subjects attended a group of IBMT at campus for 1-week with 30 min per session (a total of 3.5 h of training), while 21 control subjects received the same number and length of group sessions with relaxation training (Benson, Greenwood, & Klemchuk, 1975; Tang et al., 2007). No extra home practice was required (Tang et al., 2007).

Each IBMT or relaxation training (RT) session includes a presession (∼5 min for training preparation), a practice session (∼20 min), and a postsession (∼5 min for practice feedback and Q&A), facilitated by an experienced and certified coach, demonstrating the ability to lead the group to achieve the goal of IBMT and/or RT (Tang, Yang, Leve, & Harold, 2012; Tang et al., 2007). IBMT involves body relaxation, mental imagery and mindfulness training accompanied by a soft music background. Cooperation between the body and the mind is emphasized in facilitating and achieving a meditative state. RT involves relaxing different muscle groups over the face, head, shoulders, arms, legs, chest, back, abdomen, and so on, accompanied by soft music background. With eyes closed and in a sequential pattern, one concentrates on the sensation of relaxation, such as feelings of warmth and heaviness (See

the Training Methods in Tang et al. (2007), Tang, Rothbart, et al. (2012) and Tang, Yang, et al. (2012) for more details and examples on IBMT). Psychological mood states for all subjects of two groups before and after training were assessed using the Profile of Mood States (POMS) (Spinella, 2007; Tang et al., 2007).

2.3. EEG recording

Electroencephalography activity was recorded continuously using the Brain Products System (Brain Products GmbH, Munich, Germany) at the following 28 positions: FP1, FP2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, O1, Oz and O2. The electrode was placed according to International 10–20 System nomenclature. The EEG signal was digitized at 500 Hz. The impedance of each electrode was below 5 kΩ. An electrode placed on the vertex (FCz) served as a reference with an analog pass band of 0.01–100 Hz.

Spontaneous EEG was recorded during 5 min of quiet rest with eyes closed before and after 1-week of training. Off-line EEG data analysis was performed with commercially available software (Vision Analyzer, Brain Products GmbH, Germany). EEG data were filtered with low-pass filters at 2 Hz and high-pass filters at 50 Hz, rereferenced to the average reference. Following the previous studies (Boersma et al., 2011; Tang et al., 2009), 30 s of artifact-free data (containing no eye blinks, slow eye movements, excess muscle activity, electrocardiogram artifacts, etc.) were selected. The EEG was down sampled to 125 Hz, resulting in time series of 4096 samples for further analysis. The theta (3–8 Hz) frequency bands were analyzed.

2.4. Network analysis

In the present study, we regarded brain networks as graph representations of brain activity acquired by resting EEG data, where the vertices represented electrodes and the edges described their functional connectivity between each pair of electrodes. After extracting the time courses for each electrode, we computed the functional connectivity by synchronization likelihood (Stam & Van Dijk, 2002). For each subject, we obtained a 28×28 weighted-edge matrix of all possible (378) pair-wise combinations of electrodes. The diagonal element was self-correlation of the corresponding node and we set all the diagonal elements to 0. Graph theoretical measures were further estimated.

The average path length of a node was used to characterize how well the ith node propagated information in the network and defined as follows:

$$L_i = \frac{1}{N-1} \sum_{i \neq j} \min\{d_{ij}\}, \qquad (1)$$

in which d_{ij} was the shortest path length between the ith node and the jth node computed as the sum of the edge lengths along this path, N represented the total number of nodes ($N = 28$). As described in a previous study (Yan et al., 2011), we can likewise define the edge's length as the reciprocal of the strength of the functional connectivity.

Clustering coefficient quantified the extent to which a node's first neighborhood was a completely-connected sub-graph, and a large clustering coefficient meant high local functional overlap of densely connected neighborhood elements. In the present study, we used its definition as follows (Onnela, Saramäki, Kertész, & Kaski, 2005):

$$C_i = \frac{1}{k_i(k_i - 1)} \sum_{j,k} (w_{ij} w_{jk} w_{ki})^{1/3}, \qquad (2)$$

where k_i is the degree of node i and w_{ij} denoted the weighted edge that connected node i to node j. The clustering coefficient C of the

network is an average of C_i over all nodes. These two weight coefficients above were normalized by dividing by the maximum value across four groups of data.

Global efficiency measured integrated information processing and how well information propagates over the network. We defined global efficiency as the inverse of the harmonic mean of the shortest path length ($d_{i,j}$) between each pair of nodes. Global efficiency Eg was computed as below:

$$Eg = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d_{i,j}}. \tag{3}$$

We calculated the local efficiency of the ith node as below:

$$E_{i\_local} = \frac{1}{N_{G_i}(N_{G_i} - 1)} \sum_{j,k \in G_i} \frac{1}{d_{j,k}}, \tag{4}$$

where N_{G_i} was the number of nodes in the sub-graph G_i. Since the ith node was not an element of the sub-graph G_i, the local efficiency could also be understood as a measure of the fault tolerance of the network, indicating how well each sub-graph exchanged information when the index node was eliminated. In addition, based on its definition, it was a measure of the global efficiency of the sub-graph G_i. The local efficiency was the mean of all the local efficiencies of the nodes in the graph as below:

$$El = \frac{1}{N} \sum_{i \in G} E_{i\_local}. \tag{5}$$

3. Results

We examined changes in average path length (L) and clustering coefficient (C) of the whole weighted networks due to training. We ran a 2 × 2 repeated-measures ANOVA with group (IBMT and RT group) and training session (before and after) factors, and found group × session interactions in the average path length [$F(1,43) = 2.93$; $P = 0.09$] was marginally significant but clustering

coefficient [$F(1,43) = 0.99$; $P = 0.33$] was not significant. Before training, no differences were found between the two groups ($P > 0.05$). After training, decreased average path length ($t(23) = 3.72$, $P = 0.001$) and increased clustering coefficient ($t(23) = -2.95$, $P = 0.007$) were found following IBMT but not after RT, see Fig. 1.

Besides, we examined the weighted properties of network nodes and found the two midline electrode nodes (Fz and Pz) demonstrated a similar tendency toward shorter average path length (Fz: $t(23) = 3.17$, $P = 0.004$; Pz: $t(23) = 4$, $P = 0.006$) and larger clustering coefficient (Fz: $t(23) = -2.22$, $P = 0.04$; Pz: $t(23) = -2.1$, $P = 0.006$) after IBMT, but not after RT. The ANOVAs revealed the group × session interactions were not significant.

We used the Profile of Mood States (POMS) to measure psychological mood states in two groups. Before training, no scales of POMS showed differences between two groups ($P > 0.05$). After training, there was a significant decrease for tension–anxiety ($t(23) = 3.23$, $P = 0.0037$), depression–dejection ($t(23) = 4.10$, $P = 0.0004$), and anger–hostility ($t(23) = 2.57$, $P = 0.02$) (see Fig. 2) in the IBMT group (but not the RT group). The result was consistent with our previous study (Tang et al., 2007), indicating that 1-week IBMT can reduce negative moods. The ANOVAs revealed group × session interaction in the depression–dejection [$F(1,43) = 3.22$; $P = 0.07$] was marginally significant.

Following the previous studies (Micheloyannis et al., 2006), we investigated the topological properties of brain networks as a function of synchronization likelihood thresholds (T) ranged from 0.006 to 0.026. The weighted-edge matrices were thresholded into a set of undirected binary matrices, whose element was 1 if there was large coefficient between the two nodes, and 0 otherwise. As shown in Fig. 3, the IBMT group (not RT group) exhibited a significantly ($P < 0.05$, FDR correction for multiple comparisons) shorter average path length (see Fig. 3a, downward triangles) and larger clustering coefficient (see Fig. 3b, upright triangles) at a wide range of threshold after IBMT, in accordance with results of the above weighted analysis.
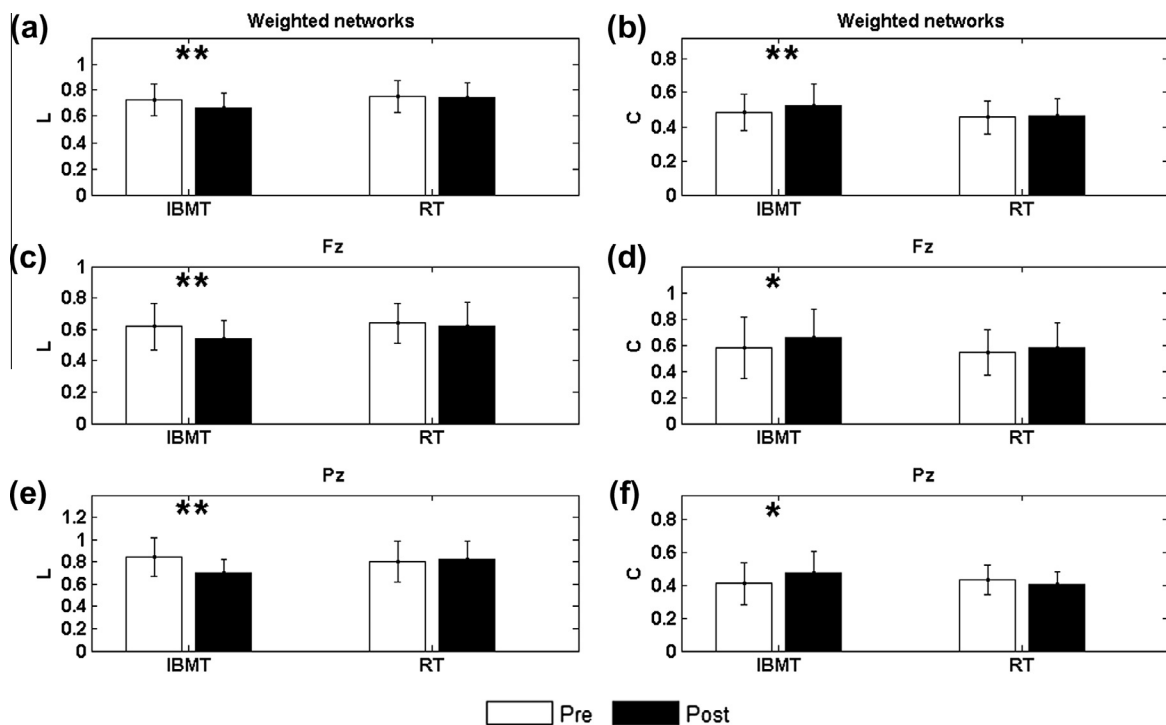

Fig. 1. Comparisons of weighted brain network properties before and after IBMT or RT. L and C are the average path length and clustering coefficient, respectively. White bars indicate pretest, black bars indicate posttest, Error bars indicate 1 SD. $^*P < 0.05$, $^{**}P < 0.01$. IBMT, integrative body–mind training; RT, relaxation training.
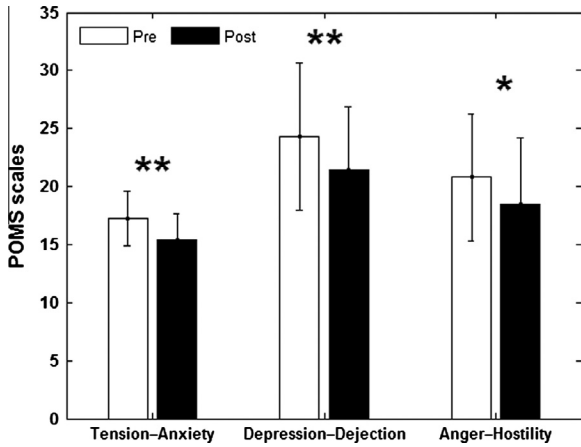
Fig. 2. Comparison of three scales of the POMS before and after training for the experimental group. Significance was found in POMS scales of tension–anxiety (TA), depression–dejection (DD), and anger–hostility (AH). No significant difference was found in other three POMS scales. Error bars indicate 1 SD. $^*P < 0.05$, $^{**}P < 0.01$. POMS (Profile of Mood States).

We employed efficiency measure to analyze both the global and local behavior of brain networks. As expected, before training, no differences were found for the two measures between the two groups ($P > 0.05$). As shown in Fig. 3c and d, efficiency monotonically decreased as a function of synchronization likelihood thresholds (T) in all networks, and the tendency of increased global and local efficiency of brain networks was found in the IBMT group (but not RT) after training ($P < 0.05$).

4. Discussion

In the present study, our results demonstrated the meditation group (IBMT) showed larger clustering coefficient, global and local efficiency, and shorter average path length after training. Shorter average path length and larger global efficiency indicate more efficient parallel information transfer by avoiding the additional noise, shortening the signaling delay and increasing synchrony in the brain, while higher clustering coefficient and local efficiency reflect the potential tendency to present communities of anatomically different regions that deal with common neural information (Iturria-Medina et al., 2011). These observations suggest that IBMT may induce clustered local connectivity with relatively few long-range connections mediating a short path length between network nodes (Achard & Bullmore, 2007), and contribute to evolvement into an optimal balance between local specialization and global integration in the brain's moment-to-moment information processing. These results are consistent with our previous findings that short-term IBMT improves cognitive performance including attention, working memory and creativity (Ding, Li, & Tang, 2011; Tang et al., 2007; Xin, Deng, Ding, & Tang, 2013).

The increase in frontal midline theta power as measured from scalp electrodes has been widely reported to correlate with meditation (Aftanas & Golocheikine, 2001; Cahn & Polich, 2006) including IBMT (Tang et al., 2009). In the present study, we found decreased average path length and increased clustering coefficient of midline electrodes (Fz and Pz) in brain networks derived from resting-state EEG theta activity due to meditation practice. As shown in Eq. (3), average path length is inversely related to the global efficiency, decreased average path length of a network node means increased its network efficiency. The findings are consistent
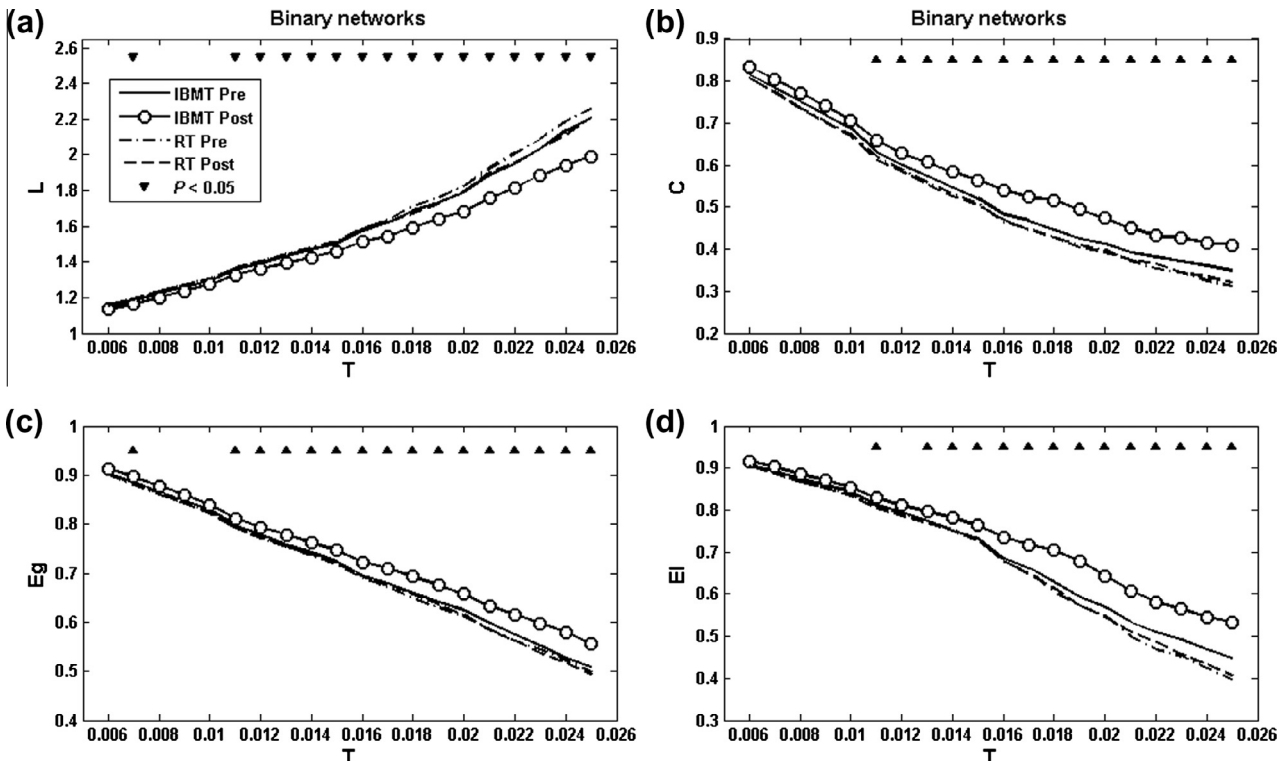

Fig. 3. Group differences in topological properties of binary brain networks before and after IBMT or RT. Changes of network measures (y-axis) are shown as a function of thresholds (x-axis) before and after 1 week of IBMT or RT. L and C are the average path length and clustering coefficient, Eg and El are global efficiency and local efficiency, respectively. Error bars correspond to standard error of the mean, black triangles indicate where the difference before and after IBMT practice is significant ($P < 0.05$, FDR correction for multiple comparisons).

with our previous results, showing that short-term IBMT increases network efficiency of the anterior cingulate cortex (Xue et al., 2011). In addition, these two midline electrodes have been regarded as source at the anterior and posterior parts of default mode network respectively. In previous fMRI studies, meditation experience is observed to be associated with changes of default mode network connectivity (Brewer et al., 2011; Jang et al., 2011; Tang et al., 2012). Our results may provide a further confirmation that meditation influences functional connectivity patterns of default mode network and then induces changes of network nodal topological properties. Further, virtually all major stimulus-driven information processing ERP effects are found along the midlines, such as P300, ERN, and CNV, suggesting the importance of midline changes associated with efficiency of information processing. More studies are warranted for interpretation of what the effects at Fz and Pz mean.

Anterior and frontal midline theta has been reported to reflect mood states and internalized attention (Cahn & Polich, 2006) as well as meditation state (Tang et al., 2009). In the present study, after training the POMS revealed less anxiety, depression, and anger only in IBMT group, indicating that 1-week IBMT can reduce negative mood (Tang et al., 2007). Moreover, the POMS results of emotional well-being are consistent with the changes in network measures of two midline electrodes.

5. Conclusion

In conclusion, we have provided the empirical support for meditation-induced network plasticity. Our results indicate the network topological pattern during resting state is altered by short-term IBMT, and may provide an interpretation of improvement of information processing in the brain. Future research is needed to explore the sequence of events in brain plasticity observed in brain networks and how they relate to the behavioral and physiological changes, as well as the longevity of such a short term experience.

Acknowledgments

References

Achard, S., & Bullmore, E. (2007). Efficiency and cost of economical brain functional networks. *PLoS Computational Biology, 3*(2), e17.

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.

Awasthi, B. (2013). Issues and perspectives in meditation research: In search for a definition. *Frontiers in Psychology, 3*, 613.

Bassett, D. S., Wymbs, N. F., Porter, M. A., Mucha, P. J., Carlson, J. M., & Grafton, S. T. (2011). Dynamic reconfiguration of human brain networks during learning. *Proczeedings of the National Academy of Sciences of the United States of America, 108*(18), 7641–7646.

Benson, H., Greenwood, M. M., & Klemchuk, H. (1975). The relaxation response: Psychophysiologic aspects and clinical applications. *The International Journal of Psychiatry in Medicine, 6*(1), 87–98.

Bishop, S. R., Lau, M., Shapiro, S., Carlson, L., Anderson, N. D., Carmody, J., et al. (2004). Mindfulness: A proposed operational definition. *Clinical Psychology: Science and Practice, 11*(3), 230–241.

Boersma, M., Smit, D., de Bie, H., Van Baal, G., Boomsma, D., de Geus, E., et al. (2011). Network analysis of resting state EEG in the developing young brain: Structure comes with maturation. *Human Brain Mapping, 32*(3), 413–425.

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

Bullmore, E., & Sporns, O. (2009). Complex brain networks: Graph theoretical analysis of structural and functional systems. *Nature Reviews Neuroscience, 10*(3), 186–198.

Burdette, J. H., Laurienti, P. J., Espeland, M. A., Morgan, A., Telesford, Q., Vechlekar, C. D., et al. (2010). Using network science to evaluate exercise-associated brain changes in older adults. *Frontiers in Aging Neuroscience, 2*, 23.

Cahn, B. R., & Polich, J. (2006). Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychological Bulletin, 132*(2), 180–211.

Ding, X. Q., Li, S., & Tang, Y. Y. (2011). Short-term meditation improves creativity. *Second World Congress on Positive Psychology*, P167.

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

Iturria-Medina, Y., Fernández, A. P., Morris, D. M., Canales-Rodríguez, E. J., Haroon, H. A., Jang, J. H., et al. (2011). Increased default mode network connectivity associated with meditation. *Neuroscience Letters, 487*(3), 358–362.

Jang, J. H., Jung, W. H., Kang, D.-H., Byun, M. S., Kwon, S. J., Choi, C.-H., et al. (2011). Increased default mode network connectivity associated with meditation. *Neuroscience Letters, 487*(3), 358–362.

Kabat-Zinn, J. (1990). *Full catastrophe living*. New York, NY: Delta Publishing.

Lazar, S. W., Kerr, C. E., Wasserman, R. H., Gray, J. R., Greve, D. N., Treadway, M. T., et al. (2005). Meditation experience is associated with increased cortical thickness. *NeuroReport, 16*(17), 1893–1897.

Luders, E., Clark, K., Narr, K. L., & Toga, A. W. (2011). Enhanced brain connectivity in long-term meditation practitioners. *Neuroimage, 57*(4), 1308–1316.

Luders, E., Toga, A. W., Lepore, N., & Gaser, C. (2009). The underlying anatomical correlates of long-term meditation: Larger hippocampal and frontal volumes of gray matter. *Neuroimage, 45*(3), 672–678.

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

Micheloyannis, S., Pachou, E., Stam, C. J., Vourkas, M., Erimaki, S., & Tsirka, V. (2006). Using graph theoretical analysis of multi channel EEG to evaluate the neural efficiency hypothesis. *Neuroscience Letters, 402*(3), 273–277.

Onnela, J. P., Saramäki, J., Kertész, J., & Kaski, K. (2005). Intensity and coherence of motifs in weighted complex networks. *Physical Review E, 71*(6), 065103.

Rubia, K. (2009). The neurobiology of meditation and its clinical effectiveness in psychiatric disorders. *Biological Psychology, 82*(1), 1–11.

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

Seeley, W. W., Crawford, R. K., Zhou, J., Miller, B. L., & Greicius, M. D. (2009). Neurodegenerative diseases target large-scale human brain networks. *Neuron, 62*(1), 42–52.

Slagter, H. A., Lutz, A., Greischar, L. L., Francis, A. D., Nieuwenhuis, S., Davis, J. M., et al. (2007). Mental training affects distribution of limited brain resources. *PLoS Biology, 5*(6), e138.

Spinella, M. (2007). Measuring the executive regulation of emotion with self-rating scales in a nonclinical population. *The Journal of General Psychology, 134*(1), 101–111.

Stam, C. J., Jones, B. F., Nolte, G., Breakspear, M., & Scheltens, P. (2007). Small-world networks and functional connectivity in Alzheimer's disease. *Cerebral Cortex, 17*(1), 92–99.

Stam, C. J., & Van Dijk, B. (2002). Synchronization likelihood: An unbiased measure of generalized synchronization in multivariate data sets. *Physica D: Nonlinear Phenomena, 163*(3–4), 236–251.

Tang, Y. Y., Yang, L., Leve, L. D., & Harold, G. T. (2012). Improving executive function and its neurobiological mechanisms through a mindfulness-based intervention: Advances within the field of developmental neuroscience. *Child Development Perspectives, 6*, 361–366.

Tang, Y. Y., Rothbart, M. K., & Posner, M. I. (2012). Neural correlates of establishing, maintaining and switching brain states. *Trends in Cognitive Sciences, 16*(6), 330–337.

Tang, Y. Y., & Posner, M. I. (2013). Theory and method in mindfulness neuroscience. *Social Cognitive and Affective Neuroscience, 8*(1), 118–120.

Tang, Y. Y., Lu, Q., Fan, M., Yang, Y., & Posner, M. I. (2012). Mechanisms of white matter changes induced by meditation. *Proczeedings of the National Academy of Sciences of the United States of America, 109*(26), 10570–10574.

Tang, Y. Y., Lu, Q., Geng, X., Stein, E. A., Yang, Y., & Posner, M. I. (2010). Short-term meditation induces white matter changes in the anterior cingulate. *Proczeedings of the National Academy of Sciences of the United States of America, 107*(35), 15649–15652.

Tang, Y. Y., Ma, Y., Fan, Y., Feng, H., Wang, J., Feng, S., et al. (2009). Central and autonomic nervous system interaction is altered by short-term meditation. *Proczeedings of the National Academy of Sciences of the United States of America, 106*(22), 8865–8870.

Tang, Y. Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., et al. (2007). Short-term meditation training improves attention and self-regulation. *Proczeedings of the National Academy of Sciences of the United States of America, 104*(43), 17152–17156.

Vestergaard-Poulsen, P., van Beek, M., Skewes, J., Bjarkam, C. R., Stubberup, M., Bertelsen, J., et al. (2009). Long-term meditation is associated with increased gray matter density in the brain stem. *NeuroReport, 20*(2), 170–174.

Williams, J. G., & Kabat-Zinn, J. (2011). Mindfulness: Diverse perspectives on its meaning, origins, and multiple applications at the intersection of science and dharma. *Contemporary Buddhism, 12*(1), 1–18.

Xin, X., Deng, Y., Ding, X., & Tang, Y. Y. (2013). Short-term meditation improves working memory performance through changing frontal-parietal network efficiency. *Psychophysiology*, S152.

Xue, S., Tang, Y. Y., & Posner, M. I. (2011). Short-term meditation increases network efficiency of the anterior cingulate cortex. *NeuroReport, 22*(12), 570–574.

Yan, C., Gong, G., Wang, J., Wang, D., Liu, D., Zhu, C., et al. (2011). Sex-and brain size-related small-world structural cortical networks in young adults: A DTI tractography study. *Cerebral Cortex, 21*(2), 449–458.