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THE NETWORK PROPERTY OF THE THALAMUS IN THE DEFAULT MODE NETWORK IS CORRELATED WITH TRAIT MINDFULNESS

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Abstract—Mindfulness is typically defined as nonjudgmental awareness of experiences in the present moment, which is beneficial for mental and physical well-being. Previous studies have identified multiple regions in the default mode network (DMN) that are involved in mindfulness, but little is known about how these regions work collaboratively as a network. Here, we used resting-state functional magnetic resonance imaging to investigate the role of the DMN in trait mindfulness by correlating spontaneous functional connectivity among DMN nodes with self-reported trait mindfulness in a large population of young human adults. Among all pairs of the DMN nodes, we found that individuals with weaker functional connectivity between the thalamus and posterior cingulate cortex (PCC) were more mindful of the present. Post-hoc analyses of these two nodes further revealed that graph-based nodal properties of the thalamus, not the PCC, were negatively correlated with trait mindfulness, suggesting that a low involvement of the thalamus in the DMN is relevant for high trait mindfulness. Our findings not only suggest the thalamus as a switch between mind-wandering and mindfulness, but also invite future studies on mechanisms of how mindfulness produces beneficial effects by modulating the thalamus.

Key words: mindfulness, default mode network, posterior cingulate cortex, thalamus, graph-based network analysis, resting-state functional connectivity.

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Abbreviations: ARAS, ascending reticular activating system; BA, Brodmann's area; DMN, default mode network; EPI, echo-planar-imaging; FDR, false discovery rate; FSL, FMRIB Software Library; GM, gray matter; LTC, lateral temporal cortex; LPC, lateral parietal cortex; MAAS, Mindful Attention Awareness Scale; MNI, Montreal Neurological Institute; MPFC, medial prefrontal cortex; MRI, magnetic resonance imaging; PCC, posterior cingulate cortex; PHG, parahippocampal gyrus; rs-fMRI, resting-state functional MRI; SD, standard deviation; SFG, superior frontal gyrus; TRL, threshold range length.

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INTRODUCTION

Experience is a steady stream that is ever flowing when we are not in a coma or deep sleep. Yet we are not always aware of what we are experiencing. Sometimes, we snack without being aware of what we eat; we hear the loudness and the beat, but do not listen to the timbre and the variation; we walk along a street, unaware of our surroundings until we step on something. At some point in our daily activities, we all "zone out." Mindfulness is typically defined as nonjudgmental or receptive awareness of and attention to experiences in the present moment (Brown and Ryan, 2003; Kabat-Zinn, 2003; Bishop et al., 2004; Brown et al., 2007). A roughly opposed construct to mindfulness is mind-wandering, which is defined as a shift of attention away from task at hand toward internal information (Smallwood and Schooler, 2006), in contrast to the fundamental component of sustained attentiveness in mindfulness. Mindfulness has become increasingly popular in both the general public and scientific community because it produces a wide range of beneficial effects on mental well-being, cognitive functioning, and physical health (Brown and Ryan, 2003; Baer et al., 2006; Cardaciotto et al., 2008; Chiesa and Serretti, 2009; Hofmann et al., 2010; Holzel et al., 2011b).

Recent neuroimaging studies indicate that the default mode network (DMN) plays a pivotal role in mindfulness. The DMN is a collection of brain regions which are typically deactivated in goal-directed tasks and activated during rest periods (Shulman et al., 1997; Gusnard and Raichle, 2001; Mazoyer et al., 2001; Raichle et al., 2001), including the precuneus/posterior cingulate cortex (PCC), medial prefrontal cortex (MPFC), lateral parietal cortex (LPC), lateral temporal cortex (LTC), parahippocampal gyrus (PHG), and thalamus (e.g., Beckmann and Smith, 2004; Fox et al., 2005; Fransson, 2005; Mantini and Vanduffel, 2013). A decade of research indicates that the DMN is involved in a variety of tasks that are generally related to mindfulness. For example, the DMN is activated during mind-wandering (Mason et al., 2007; Christoff et al., 2009; Dickenson et al., 2013), self-referential processing (Northoff et al., 2006; Herwig et al., 2010), stimulus-independent thoughts (Buckner et al., 2008; Buckner, 2012), and retrieving memories and envisioning the future (Schacter et al., 2007; Andrews-Hanna et al., 2010; Spreng and Grady, 2010).

More specifically, empirical exploration of mindfulness has mainly focused on cultivation of mindfulness by meditation practice (Baer, 2003; Kabat-Zinn, 2003).

Functional magnetic resonance imaging (MRI) studies have demonstrated differences in the DMN activations between experienced meditators and novices. Nevertheless, it is unclear whether meditation training is related to increased or decreased activation of the DMN. For example, the MPFC and PCC are deactivated in both long-term meditators when they view emotional pictures in a mindful state (vs. a non-mindful state) (Taylor et al., 2011) and short-term meditators (after 8-week meditation training) when they attend to the present experience (vs. attend to enduring traits) (Farb et al., 2007). On the other hand, the MPFC shows increased activation in monks during meditation (vs. rest), but not in novices (Manna et al., 2010). The discrepancy of these results is likely due to differences in experimental and baseline tasks employed during scanning, duration of training, and participant characteristics. The findings of structural MRI studies are more consistent, with several cross-sectional studies reporting greater gray matter (GM) volume or density of the DMN regions in meditators than novices, including the PCC, LTC, LPC, PHG, and thalamus (Holzel et al., 2008; Luders et al., 2009; Leung et al., 2013). Further, one longitudinal study showed that the GM density in the PCC is enlarged after 8 weeks of mindfulness training (Holzel et al., 2011a). Finally, meditation training is associated with differences in functional connectivity between DMN nodes comparing meditators with novices (Brewer et al., 2011; Jang et al., 2011; Taylor et al., 2013). In short, mindfulness meditation is related to both function and structure of the DMN regions.

A growing number of studies have conceptualized mindfulness as a dispositional characteristic, i.e. trait mindfulness, which varies naturally across individuals even without mindfulness practice (Brown and Ryan, 2003). Although there is some debate over whether trait mindfulness and trained mindfulness represent the same construct and share the same neural basis (e.g., Davidson, 2010), previous neuroimaging studies on trait mindfulness also indicate the involvement of the DMN. For example, trait mindfulness is negatively correlated with resting-state activity in the PCC (Way et al., 2010) and self-referential processing activity in the MPFC (Herwig et al., 2010). And a recent structural MRI study found that trait mindfulness negatively correlated with GM volume in the PCC (Lu et al., 2014). However, it is unclear how the collaboration between the DMN nodes reflects trait mindfulness.

Here, we aimed to address two questions. First, what is the relationship between trait mindfulness and functional connectivity of the DMN nodes? Second, what is the relevant node for trait mindfulness in the DMN? To address these questions, we first acquired resting-state functional MRI (rs-fMRI) data and assessed trait mindfulness in a large population of young adults ($N = 245$). Because awareness of the present experience is a fundamental element in all definitions of mindfulness, we adopted the Mindful Attention Awareness Scale (MAAS) (Brown and Ryan, 2003), a widely used self-reported measure of trait mindfulness in the literature, to assess mindfulness as a dispositional general tendency to ‘‘be attentive to and aware of present-moment experiences’’ (Brown and Ryan, 2003). We then explored the role of the DMN in self-reported trait mindfulness by correlating the functional connectivity among DMN nodes with MAAS scores across individuals. Finally, we used graph-based network analyses to identify the relevant node for trait mindfulness in the DMN.

EXPERIMENTAL PROCEDURES

Participants

Two hundred and forty-five (129 females and 116 males; 18–25 years of age, mean age = 21.7 years, standard deviation [SD] = 1.05) college students from Beijing Normal University, Beijing, China, participated in the study. Participants with self-reported history of medication and neurological or psychiatric disorders were excluded. Both behavior and fMRI protocols were approved by the Institutional Review Board of Beijing Normal University. Informed written consent was obtained from all participants before the experiment. Note that the participants in the current study were a subset of the sample in a previous voxel-based morphometry (VBM) study on trait mindfulness (Lu et al., 2014).

Measuring mindfulness

Trait mindfulness was assessed by the MAAS, which is a well-established self-report questionnaire with excellent internal consistency and test–retest reliability (Brown and Ryan, 2003). The MAAS contains 15 items with a single factor, and exemplar items are ‘‘I find it difficult to stay focused on what's happening in the present,’’ and, ‘‘I find myself preoccupied with the future or the past.’’ Participants rate each MAAS item on a 6-point Likert-type scale (1 = almost always, 6 = almost never), and the MAAS score, which is calculated by averaging the participant's scores for the 15 items, is used as the index for a participant's trait mindfulness. The MAAS score ranges from 1 (mind-wandering) to 6 (mindful). Outliers were defined as being three SDs below or above the population mean of the MAAS score. One male participant (0.4% of the participant population) was excluded from further analyses because his MAAS score was three SDs below the mean. All participants completed the MAAS in a separate session after the MRI scan. Because the acquisition of MRI data was time-consuming for the large sample of participants, the MAAS was measured at least a month after MRI data acquisition. Given that the temporal stability of trait mindfulness as measured by the MAAS scale has been shown over a month (Brown and Ryan, 2003), the time interval may have little impact on the results in the present study.

rs-fMRI data acquisition and preprocessing

The rs-fMRI scan was performed on a 3T scanner (Siemens Magnetom Trio, A Tim System) with a 12-channel phased-array head coil at Beijing Normal University Imaging Center for Brain Research, Beijing, China. Participants were instructed to relax without engaging in any specific task and to remain still with their