CHAPTER 10

The Neurobiology of Mindfulness Meditation

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For thousands of years, contemplatives have reported that enhancements in sensory awareness, cognition, and health can be accomplished through meditation practice. Before the development and utilization of neuroimaging and other scientific methodologies, the scientific world cast these descriptions as reflections of a relaxation response at best, and report biases associated with practitioner zeal at worst. The recent surge in number of mindfulness-based studies has supported the claim that mindfulness meditation can improve a range of mental and physical health outcomes, and neuroimaging studies are beginning to identify the brain mechanisms that mediate the relationships between mindfulness meditation and such outcomes. Although the neuroscientific investigation of mindfulness meditation is in its infancy, the premise of this chapter is that mindfulness meditation engages a unique, distributed network of brain regions.

Recent accounts of mindfulness meditation have delineated some of the psychoneurobiological mechanisms of action of this method of mental training (Austin, 1998; Cahn & Polich, 2006; Hölzel et al., 2011) and offered theoretical frameworks to describe and explain meditation-based changes in neurocognitive and self-related processes (Vago & Silbersweig, 2012). However, discrepancies between meditation traditions, and differing characteristics and durations of training highlight the importance of delineating the neurobiological mechanisms of mindfulness meditation from a longitudinal perspective. Therefore, a comprehensive description of the brain mechanisms supporting mindfulness meditation must consider commonalties and differences across training levels. This chapter builds on previous neuroscientific work by offering a complementary perspective that focuses on a temporal account of the neurobiology of mindfulness, which considers the neurobiological basis of *how* mindfulness engages the brain over time. In this chapter, I first provide a brief overview describing some key neuroimaging methodologies used in research. In the sections to follow, I provide a descriptive account of the neurobiological correlates of dispositional mindfulness, brief meditation training (1 week or less), the mindfulness-based stress reduction (MBSR) program (approximately 8 weeks), and finally expert meditators (more than 1,000 hours of practice). The subsequent section, concerning mindfulness and the default mode network, briefly describes how different levels of mindfulness-related experience affect task-independent neural processing. I then provide a longitudinal perspective of the brain structural correlates associated with different levels of mindfulness. Finally, I discuss considerations for future mindfulness-based and other contemplative practice research.

A Stage-Based Account of the Neurobiology of Mindfulness Meditation

In this chapter, I argue that the neurobiology of mindfulness varies across different levels of meditation training (Figure 10.1). The proposed neurobiological model of mindfulness meditation is quite consistent with and based on the underlying principles of mindfulness postulated to develop across varying levels of proficiency in different meditative practice traditions (Gunaratana, 2002; Lutz, Slagter, Dunne, & Davidson, 2008; Wallace, 2006). I propose that mindfulness meditation is associated with higher-order brain mechanisms such as the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC) at early stages of this form of mental training. This pattern of neural activity is also evident in those who have never meditated, but whose reports indicate higher levels of trait mindfulness. Because some accounts of mindfulness meditation are based on attending to arising sensory events, sensory appraisal-based brain regions such as the anterior insula and the somatosensory cortices are activated across all meditation training levels. However, at early stages of mindfulness meditation training and development, practitioners engage brain mechanisms supporting an effortful top-down regulation of lower-level afferent processing, indicated by greater activation in the PFC and ACC and deactivation of the thalamus and the amygdala, brain regions involved in early stages of sensory and emotional processing, respectively. As the meditator becomes more skilled at attending to sensory and emotional experiences without interpretation or elaboration, a decoupling between brain mechanisms supporting appraisals of sensory processing develops, as indicated by decreases in higher-order brain activity (PFC) and increases in sensory-processing brain regions (anterior insula, somatosensory cortices). I also postulate that robust changes in brain structure are associated with extensive training in mindfulness meditation and higher levels of dispositional mindfulness. Some initial studies *suggest* that mindfulness meditation can offset and/or buffer against age-related cortical thinning (Grant, Courtemanche, Duerden, Duncan, & Rainville, 2010; Hölzel et al., 2008; Lazar et al., 2005). In fact, adept meditation practitioners exhibit significant reductions in neural structures associated with emotional processing (amygdala) and increased thickness in brain regions associated with sensory awareness (insula). These findings suggest that long-term training in mindfulness meditation

	Behavioral mechanisms	Brain mechanisms
Trait mindfulness	Labeling emotions as they arise Cognitive reappraisal Reduced mind-wandering	↑ PFC → ↓ Amygdala ↓ Default-mode network
Brief meditation training (<1 week)	Cognitive reappraisal Reduced mind wandering Interoceptive awareness Reward processing	↑ OFC, rACC, pgACC, right anterior insula, S2, SI corresponding to breathing ↓ Thalamus, default-mode network, amygdala
MBSR (8 weeks): State effects	Interoceptive awareness Sensory evaluation Cognitive control	↑ PFC, right anterior insula, S2
MBSR (8 weeks): Trait effects	Interoceptive awarness Working memory Cognitive control of emotion	↑ Gray matter in the hippocampus, PCC, TPJ ↓ Gray matter in the amygdala
Expert meditators (>1,000 hours of meditation training)	Interoceptive awareness Cognitive control of emotion Sensory evaluation Reward Processing Reduced mind-wandering	↑ rACC, PFC, putamen, anterior insula ↓ Default-mode network
Expert meditators (>1,000 hours of training): Trait effects	Higher sensory processing Reduced evaluation/appraisals Reduced mind-wandering Interoceptive awareness	↑ Thalamus, S2, posterior insula ↑ Gray matter in S2, posterior insula, right anterior insula ↓ PFC ↓ Default-mode network

FIGURE 10.1. Current understanding of the neurobiology of mindfulness meditation. *First row:* Trait mindfulness has been associated with cognitive reappraisal processes and interoceptive awareness. The neural correlates of these behavioral outcomes are reflected in downregulation of the amygdala by the prefrontal cortex (PFC) as well as reduced default-mode network activation. *Second row:* Meditating after brief meditation training engages brain mechanisms supporting reduced mind wandering (default-mode network) and amygdala activation (emotional processing), and greater activation in brain regions involved in reward processing (orbitofrontal cortex [OFC]), cognitive control and emotion regulation (OFC, rostral anterior cingulate cortex [rACC], perigenual ACC [pgACC]), sensory evaluation (secondary somatosensory cortices [S2]), and interoceptive awareness (right anterior insula). *Third row:* After training in mindfulness-based stress reduction (MBSR) programs, meditation produces brain activation in the PFC (cognitive control), right anterior insula (interoceptive awareness), and S2 (sensory evaluation). Stabilized, trait-like effects associated with MBSR (*fourth row*) are associated with reducing structural gray-matter density in the amygdala (emotional processing), and increasing gray-matter density in the hippocampus (working memory), temporoparietal junction (TPJ), and posterior cingulate cortex (PCC), brain regions associated with self-referential processes. Adept meditators show activation in the rACC, right anterior insula, putamen, and PFC during meditation (*fifth row*) and deactivation in the default mode brain network. Long-term changes in expert meditators (*sixth row*) are reflected by increases in gray matter and regional blood signals in sensory processing brain regions (S2, thalamus, posterior insula), and reduced activation in higher-order evaluative neural regions (PFC) and the default mode network.

may produce stabilized, “plastic” changes that can potentially support mindfulness-related enhancements in cognition and health. Taken together, the proposed model (Figure 10.1) provides an initial neurobiological account for the ways in which mindfulness meditation differentially engages a unique set of brain regions across different stages of meditative training. Before turning to the evidence for this model, I first briefly describe the neuroscientific methods used in mindfulness meditation-related research (for more, see He, Yang, Wilke, & Yuan, 2011; Howseman & Bowtell, 1999; Tang & Posner, Chapter 5, this volume).

Overview of Neurophysiological Methodologies

Mindfulness-based neuroscience has used two primary neurophysiological methods to identify the brain mechanisms associated with meditation. First, electroencephalography (EEG) uses electrodes placed on the scalp to record activity of electrical currents produced by neural synaptic activity. The event-related potential (ERP) is a neural marker embedded within continuous EEG signals that corresponds to a singular (predetermined) external event (i.e., attending to an exogenously driven stimulus). Although the spatial resolution of EEG/ERP is not very high, it is suitable for capturing *when* a cognitive and/or sensory event occurs; that is, it has high temporal resolution, on the order of milliseconds.

The development of neuroimaging methods, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and arterial spin labeling (ASL) fMRI, has provided means to collect direct (perfusion-based fMRI; PET) and indirect (blood oxygen level–dependent [BOLD]; fMRI) measures of cerebral blood flow (CBF), which provide higher spatial resolution (i.e., indicating where neural activity may be occurring), although this comes at a tradeoff, with poorer temporal resolution (2–5 seconds) than EEG/ERP.

Neural Correlates of Dispositional Mindfulness

Although the focus of this chapter is on delineation of the neural mechanisms supporting the effects of mindfulness meditation across different mental training levels, it is important to recognize that self-reported dispositional mindfulness is also associated with engaging a unique set of brain mechanisms. In the research community, dispositional mindfulness is measured in a basic way and is typically considered an inherent ability to sustain nonevaluative attention and/or receptive awareness to ongoing events and experiences. Not surprisingly, there is considerable interindividual variability in this capacity, and such differences have been associated with mindfulness theory-consistent neurobiological and other outcomes. For example, individuals reporting higher levels of dispositional mindfulness exhibit reduced neuroendocrine stress reactivity (Brown, Weinstein, & Creswell, 2012; Ciesla, Reilly, Dickson, Emanuel, & Updegraff, 2012; Tamagawa et al., 2013), lower amygdala activity at rest (opposed to those reporting higher depressive symptoms) (Way, Creswell, Eisenberger, & Lieberman, 2010), fewer posttraumatic stress symptoms (Garland & Roberts-Lewis, 2013), better sleep quality and physical health (Murphy, Mermelstein, Edwards, & Gidycz, 2012), and report higher psychological well-being (Brown & Ryan, 2003).

A growing body of neuroscientific research on dispositional mindfulness also suggests that this quality of attention promotes emotion regulation, a key underpinning of the mental and physical health outcomes just noted. The PFC is involved in the metacognitive ability to identify and/or label ongoing subjective experiences (Cole & Schneider, 2007; Ochsner et al., 2004; Wager, Davidson, Hughes, Lindquist, & Ochsner, 2008). Top-down regulation of the amygdala, a brain region crucially involved in fear processing (LeDoux, 2013), anxiety, and affect (Bishop, 2007, 2009; Urry et al., 2006) by the PFC, has been implicated as a classical neural signature of cognitive reappraisal processes (i.e., reinterpreting the meaning of a sensory event) that are considered an important, adaptive form of emotion regulation (Banks, Eddy, Angstadt, Nathan, & Phan, 2007; Drabant, McRae, Manuck, Hariri, & Gross, 2009; Goldin, McRae, Ramel, & Gross, 2008). In a seminal study, Creswell, Way, Eisenberger, and Lieberman (2007) revealed that greater dispositional mindfulness was associated with greater top-down regulation of the right amygdala by the ventrolateral PFC (vlPFC) during an emotion regulation task (i.e., affect labeling). Moreover, some studies indicate that mindful individuals exhibit a unique form of cognitive reappraisal (Garland, Gaylord, & Park, 2009; Garland et al., 2010; Shapiro, Carlson, Astin, & Freedman, 2006; Vago & Silbersweig, 2012; Zeidan, Martucci, Kraft, McHaffie, & Coghill, 2014), namely, the cognitive ability to disengage from higher-order interpretations of sensory events while maintaining an objective cognitive stance. After instructing participants to reappraise negative emotion-inducing pictures (International Affective Picture System [IAPS; Lang, Bradley, & Cuthbert, 1997]), Modinos, Ormel, and Aleman (2010) found that participants higher in dispositional mindfulness were more successful at regulating affective responses to negative mood-inducing pictures. Modinos and colleagues, similar to Creswell and colleagues (2007), found that mindful subjects reappraising negative stimuli showed higher PFC activation (i.e., dorsomedial PFC [dmPFC]), which in turn was associated with less activity in the amygdala. Higher dispositional mindfulness appears to reflect top-down regulation of brain regions involved in early stages of emotional processing (Brown, Goodman, & Inzlicht, 2013), mechanisms also seen in later stages of mindfulness development (through meditation training; see Figure 10.1). Interestingly, we have found that self-reported mindfulness can be significantly increased (up to 16%) after only 3 or 4 days of mindfulness meditation training (Zeidan, Gordon, Merchant, & Goolkasian, 2010; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010; Zeidan et al., 2011), suggesting that mindfulness-induced top-down regulation of affective processes can be enhanced even after brief mental training, an important consideration for the clinical utility of mindfulness.

Neural Correlates of Brief Training in Mindfulness Meditation

In this chapter, I propose (Figure 10.1) that brief training in mindfulness meditation engages brain mechanisms that support unique cognitive reappraisal processes that are involved in higher-order cognitive and affective control, enhanced interoceptive and sensory evaluation, acceptance-based emotion regulation, and reductions in low-level afferent processes (Taylor et al., 2011, 2013; Zeidan et al., 2011, 2014). Brief mindfulness training (1 week or less of training) has also led to improvements across a wide spectrum of cognitive (Mirams, Poliakoff, Brown, & Lloyd, 2013; Tang et al., 2007, 2009; Zeidan, Johnson, Diamond, et al., 2010), pain, and stress reduction outcomes (Tang, Tang, & Posner, 2013; Zeidan, Johnson, Gordon, & Goolkasian, 2010; Zeidan et al., 2011, 2014). Using perfusion fMRI, we recently assessed the brain mechanisms supporting mindfulness meditation, the neural correlates of meditation-related pain attenuation, and anxiety relief after a brief mental training intervention (4 days, 20 minutes per day) that involved breath awareness and other Vipassanā-based meditation techniques (Zeidan et al., 2011). Across 4 days, healthy, pain-free subjects were taught to focus on the changing sensations of the breath and to “acknowledge” sensory events nonjudgmentally. Regarding the brain mechanisms supporting mindfulness meditation, our findings revealed that this training engaged multiple brain regions that process executive level cognitive control (PFC, ACC) and sensory evaluation (anterior insula; secondary somatosensory cortices). Meditation activated the bilateral orbitofrontal cortex (OFC), a brain region involved in reframing the interpretation of our sensory experiences (O’Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; Peters & Buchel, 2010; Rolls & Grabenhorst, 2008; Schoenbaum, Takahashi, Liu, & McDannald, 2011). We also detected widespread activation of the ACC, specifically the rostral ACC (rACC) and perigenual ACC (pgACC), during meditation, replicating previous findings with other novice meditators (Manna et al., 2010). Regarding pain attenuation, greater meditation-related activation in aspects of the ACC was directly associated with reducing pain and state anxiety ratings (Zeidan et al., 2011, 2014). Regarding anxiety relief, regression analyses revealed that brain activation corresponding to meditation-related pain relief was different than that associated with meditation-induced anxiety reductions (Zeidan et al., 2014). Importantly, meditators uniquely activated brain regions associated with attending to ongoing sensory events. For instance, significant activation in the right anterior insula, a brain region associated with processing sensory experiences relating to the self (Critchley, 2004; Critchley, Wiens, Rotshtein, Ohman, & Dolan, 2004), and the primary somatosensory cortex (S1), corresponding to the somatotopographic representation of the nose and mouth (where subjects were taught to direct their attention), were significantly activated during meditation. Meditation also activated lower-level sensory processing regions such as the bilateral secondary somatosensory cortices (S2; Coghill, Gilron, & Iadarola, 2001). In summary, this research suggests that even brief and basic training in mindfulness meditation is associated with processing sensory information (S2, anterior insula) and the engagement of brain mechanisms (OFC, ACC) involved in the cognitive reappraisal of sensory information (O’Doherty et al., 2001; Rolls & Grabenhorst, 2008).

Considerable insight into the mechanisms involved in the neurobiology of mindfulness meditation can be gained by examining how meditation modulates nociceptive (painful, noxious) processing. Pain is constructed and modulated by a constellation of interactions among sensory, cognitive, and affective dimensions of our moment-to-moment subjective experience, the same factors that are modulated by mindfulness meditation. My colleagues and I found that mindfulness meditation, after 4 days of mental training, significantly attenuated S1 activation, corresponding to painful stimulation (right calf) (Zeidan et al., 2011). Furthermore, regression analyses revealed that meditation-related pain relief was associated with significant reductions in low-level nociceptive processing, evidenced by widespread thalamic deactivation. Within the same set of analyses, meditation-related pain relief was associated with increases in executive level brain regions, including the OFC and ACC. These findings illustrate that mindfulness meditation modulates ascending sensory information at thalamic levels before accessing cortical regions implicated in interpreting the meaning of afferent information (Crick, 1984).

Other studies assessing the effects of brief meditation training on neural processes in response to emotion-provoking experimental tasks reveal similar mechanisms corresponding to top-down regulation of lower-level afferent processing. For example, using BOLD fMRI, Taylor and colleagues (2011) examined behavioral and neural responses to emotion-inducing IAPS pictures (Lang et al., 1997) in a group of naive meditators after 7 days of self-facilitated mindfulness meditation training (i.e., listening to an audio recording of guided mindfulness meditation). When compared to attending to "neutral" pictures, "mindfully attending" to positive and negative emotion-inducing pictures produced significant activation in brain regions involved in cognitive control of emotion (e.g., medial PFC [mPFC], lateral PFC, rACC), interoceptive awareness (anterior insula), working memory (hippocampus), as well as deactivation of the amygdala. This network of brain activity was associated with reports of reduced emotional intensity when attending to negative and positive affect-inducing stimuli. Taken together, these findings reveal that brief training in meditation activates the ACC and the PFC to regulate lower-level, emotionally salient sensory processing. These findings also indicate that mechanistic distinctions between self-reported dispositional mindfulness and mindfulness meditation exist. For instance, while PFC activation during mindfulness meditation is similar to brain activity associated with dispositional mindfulness, activation in the ACC and sensory processing areas (anterior insula, somatosensory cortices) signify that the cognitive state of meditation engages brain regions associated with unique, effortful, and purposeful attention toward sensory and cognitive processes. However it bears noting that there are still comparatively few neuroscientific studies of both dispositional mindfulness and brief mindfulness training. As we will see, the neurobiological changes induced by mindfulness meditation after brief training are quite consistent with neural changes seen in mindfulness practitioners trained in the 8-week MBSR course.

Neural Correlates of Mindfulness Meditation after 8-Week MBSR Training

The MBSR program is an 8-week, intensive meditation course (Kabat-Zinn, 1990) that involves weekly guided group meditation sessions, daily guided meditation exercises practiced at home with the aid of audio recordings (e.g., focusing on the breath and body sensations as the meditative object), and a daylong meditation retreat conducted largely in silence. MBSR has been shown to improve a variety of mental and physical health outcomes (Grossman, Niemann, Schmidt, & Walach, 2004). Similar to brief meditation training, MBSR has been shown to activate brain regions implicated in executive-level processes (Figure 10.1). For example, evidence for neural processes involved in MBSR-related improvements has been found in clinical anxiety (patients with generalized anxiety disorder), with training-related reductions in amygdala activity (Goldin & Gross, 2010; Goldin, Manber-Ball, Werner, Heimberg, & Gross, 2009) and activation in brain regions supporting reappraisal (i.e., aspects of the PFC and rACC) (Goldin, Ziv, Jazaieri, & Gross, 2012; Goldin & Gross, 2010; Goldin et al., 2009; P. Goldin, Ziv, Jazaieri, Hahn, & Gross, 2013).

Studies assessing the efficacy and neural correlates of MBSR participation in healthy adults paint a similar picture. When instructed to mindfully attend to the sounds of the MRI scanner, Kilpatrick and colleagues (2011) revealed that meditation induced robust functional-neural connections between the bilateral anterior/posterior insula, the mPFC, and ACC. Attending to one's internal bodily sensations after MBSR produced significant activation in right-lateralized vlPFC, ventromedial PFC (vmPFC), anterior insula, and S2, brain areas previously associated with practicing mindfulness meditation (Farb et al., 2007). Comparing the effects of breath awareness in a group that completed an MBSR program with a wait-listed control group, Farb, Segal, and Anderson (2013) found through functional connectivity analyses a robust decoupling between the insula and mPFC. Whereas the right anterior insula processes interoceptive awareness (Critchley, 2004; Critchley et al., 2003, 2004), the mPFC is a central neural hub for integrating self-narrative thought processes. These findings suggest that participation in an 8-week MBSR course can produce conscious processing changes reflecting a shift from a self-focused mental stance to a more receptive, less evaluative engagement of ongoing sensory events (Farb et al., 2013), neural markers associated with adept meditators, which I discuss next.

Neural Correlates of Long-Term Mindfulness Meditation Training

The neuroscientific investigation of adept meditators (more than 1,000 hours of practice; Taylor et al., 2011) suggests that long-term mindfulness meditation training significantly changes the manner in which sensory and perceptual processing occurs in the brain. Whereas brief meditation training appears to produce activation in executive-level brain regions (e.g., PFC) and reductions in lower-level sensory processing, evidenced by deactivations in the thalamus and primary somatosensory cortices, here I propose (Figure 10.1) that long-term meditators exhibit neural activity associated with higher-order awareness reflecting a greater acceptance of sensory experiences without the contextual elaboration or interpretation of those respective events. Indeed, some initial studies suggest that this proposed *shift* in cognitive processing is positively correlated with cumulative time spent in meditation practice (Brefczynski-Lewis, Lutz, Schaefer, Levinson, & Davidson, 2007; Brown & Jones, 2010; Froeliger et al., 2012; Grant et al., 2010; Grant & Rainville, 2009; Hasenkamp & Barsalou, 2012; Lazar et al., 2000; Lutz, Greischar, Rawlings, Ricard, & Davidson, 2004; Saggar et al., 2013). The proposed *shift* in cognition between brief and extensive training can be first demonstrated during formal meditation practice. While beginning stages of mindfulness practice tend to reflect a more effortful, self-directed attentional and emotion-regulatory stance, long-term meditators are postulated to meditate with more efficiency and less effort (Brewer et al., 2011; Gard et al., 2011; Grant, Courtemanche, & Rainville, 2011; Lutz et al., 2008; Manna et al., 2010; Zeidan, Grant, Brown, McHaffie, & Coghill, 2012). Additionally, the neural changes corresponding to adept meditators are more stabilized, such that the cognitive *state* of mindfulness meditation has been transformed into a *trait* or temperament that continues outside of formal mindfulness meditation practice (Davidson et al., 2003; Dunne, 2011; Grant et al., 2011; Lutz, McFarlin, Perlman, Salomons, & Davidson, 2013).

During mindfulness meditation practice, long-term meditators exhibit *increased* activation in brain regions associated with (1) cognitive control, indexed by the rACC (Baerentsen et al., 2010; Brewer et al., 2011; Hölzel et al., 2007; Manna et al., 2010; Short et al., 2010) and aspects of the PFC (superior frontal gyrus, middle frontal gyrus, dlPFC; Baerentsen et al., 2010; Brefczynski-Lewis et al., 2007; Manna et al., 2010); (2) brain regions involved in reward processing (putamen; Baerentsen et al., 2010; Brefczynski-Lewis et al., 2007); and (3) sensory processing (anterior insula; Brewer et al., 2011; Hasenkamp & Barsalou, 2012; Manna et al., 2010). Findings from EEG studies reveal that long-term meditation practitioners process sensory information more quickly after stimulus presentation (Cahn & Polich, 2009), with reduced interference from distracting stimuli (Cahn, Delorme, & Polich, 2013; Cahn & Polich, 2009; Lutz, Slagter, et al., 2009; Slagter et al., 2007), reflecting an overall improvement in perceptual and attentional stability (Lutz et al., 2004; Maclean et al., 2010). These findings provide further evidence that extensive meditation practice can alter cognitive processing, indicated by brain activity corresponding to higher-level executive cognitive control, enhanced lower-level sensory processing, and reduced influences of distracting sensations.

One of the underlying principles of mindfulness-based mental training is the attenuation of affective interpretations (Gunaratana, 2002; Nhât Hanh, 1987; Shapiro et al., 2006). Neuroimaging research focused on elucidating the neural correlates of meditation-related pain relief revealed that long-term meditation practitioners exhibit a less evaluative cognitive stance, demonstrated by reductions in the dlPFC, in the presence of intrusive, painful stimulation (Gard et al., 2011; Grant et al., 2011; Lutz et al., 2013), while brain regions involved in lower-level sensory processing (S2, thalamus; posterior insula) were significantly activated. Interestingly, this decoupling between brain regions supporting appraisal-oriented and sensory processing was directly related to lower pain reports (Gard et al., 2011; Grant et al., 2011). Reductions in the interpretation of the subjective pain experience are associated with reduced anticipation of impending sensory stimuli (Brown & Jones, 2010; Gard et al., 2011; Lutz, Greischar, Perlman, & Davidson, 2009; Zeidan et al., 2012). While the neural correlates of meditation are quite similar between brief meditation training and long-term training, the transformative neural changes associated with long-term meditation practice have been most clearly exhibited when practitioners are instructed to attend to intrusive sensory events in a nonmeditative state or at rest. This is where we see a greater disengagement between higher-order and lower-level appraisal brain mechanisms, reflecting a temperamental change in higher-level sensory awareness that resembles the cognitive state of meditation but which, taking trait form, appears more stable and enduring.

Mindfulness and the Default Mode Network

The default mode network of the brain is characterized by a robust pattern of oscillating neural activity among the mPFC, posterior cingulate cortex (PCC)/precuneus, and medial parietal cortices, and is activated (and functionally connected) during passive resting states, such as passively viewing a fixation cross (Buckner, 2012; Fransson & Marrelec, 2008; Raichle et al., 2001; Scheeringa et al., 2008). The way in which meditation practitioners experience passive resting states (default mode, network-related cognitive processing) differs from that of nonmeditators, and suggests an enhanced capacity to engage moment-to-moment awareness in a nonjudgmental manner. The neural findings to date suggest that that meditators actively engage ongoing sensory events, with an accompanying significant reduction in mind wandering and self-referential evaluations that have been associated with negative mood states (Killingsworth & Gilbert, 2010; Smallwood, Fitzgerald, Miles, & Phillips, 2009). Some of the most common patterns of neural activity across meditative training levels are reflected within the default mode network (Figure 10.1). Reductions in default mode network activation during meditation are reported in studies examining all three forms of training discussed here: brief meditation training (Taylor et al., 2013; Zeidan et al., 2011), 8 weeks of MBSR training (Farb et al., 2007, 2010), and long-term meditation practice (Brewer et al., 2011; Garrison et al., 2013; Grant et al., 2011; Pagnoni, 2012). While we found that greater meditation-related reductions in neural activation in aspects (PCC) of the default mode network were associated with lower anxiety reports after brief mental training (Zeidan et al., 2013), others have found that long-term meditators report significant reductions of mind wandering, with corresponding reductions in default-mode network brain activity, even during rest and when compared to novice meditators (Taylor et al., 2013). These findings support the notion that while all levels of mindfulness significantly reduce default mode related brain activity, only extensive mindfulness practice over years produces durable changes in moment-to-moment processing and corresponding neural activity.

Structural Correlates of Mindfulness: A Longitudinal Perspective

Mindful individuals and mindfulness meditation practitioners have recently been found to exhibit unique differences in brain structures when compared to controls, or to individuals reporting lower levels of mindfulness. In one of the largest known mindfulness and neuroimaging studies (155 participants), Taren, Creswell, and Gianaros (2013) revealed that higher trait mindfulness levels were associated with smaller gray-matter volumes in right-lateralized amygdala and left-sided caudate, brain regions associated with processing a wide spectrum of emotions. The structural density and gray-matter concentrations of the amygdala and other brain regions in dispositionally mindful individuals parallel the effects observed in meditation practitioners. Moreover, highly stressed individuals assessed before and after an 8-week MBSR course showed significant reductions in reported perceived stress, and these were associated with reductions in the right amygdala gray-matter density (B. K. Holzel et al., 2010). Increases in gray-matter concentrations in the left hippocampus, PCC, temporopartietal junction, and cerebellum have also been exhibited after MBSR participation (Hölzel et al., 2008). These findings may mark the beginning stages of more stable neural and behavioral improvements exhibited by adept meditators. In fact, studies assessing structural changes in long-term meditators have found significant increases in cortical thickness in sensory processing regions such as the dorsal ACC, bilateral S2 (Grant et al., 2010), S1, and right anterior insula (reflecting greater self-awareness) (Lazar et al., 2005), when compared to controls (Hölzel et al., 2010, 2011).

Building Models of the Mindful Brain: Opportunities and Challenges

There are still significant gaps in our understanding of the neurobiology of mindfulness. For one, we have yet to determine the neurofunctional connections mediating the relationship between mindfulness meditation and improvements in mental health. There are aberrant functional connections corresponding to brain regions associated with self-referential processing and disorders such as depression (Anand et al., 2005; Sheline, Price, Yan, & Mintun, 2010; Zeng et al., 2012), chronic pain (Loggia et al., 2013), and addiction (Konova, Moeller, Tomasi, Volkow, & Goldstein, 2013; Sutherland, McHugh, Pariyadath, & Stein, 2012). Since mindfulness meditation has been found to improve several mental health outcomes significantly (Brewer, Elwafi, & Davis, 2013; Farb et al., 2010; Kabat-Zinn, Lipworth, & Burney, 1985; Westbrook et al., 2013), it would be fruitful to determine whether such meditation-related improvements are directly associated with changes in neurofunctional connectivity. We also have not determined the active neurotransmitters corresponding to mindfulness meditation-related improvements in mental health. Bridging these explanatory gaps may advance the field to understand how meditation improves health. Additionally, we still do not know how mindfulness meditation practice leads to more stabilized temperamental neural effects exhibited by long-term practitioners. In other words, how much training is needed before we see long-lasting changes in the brain? Must training be ongoing for such changes to endure?

Another important issue in neuroscientific investigations of meditation deals with the significant reduction in respiration rate during meditation and how this may affect neuroimaging measures of neural activity. In short, meditation alters respiration patterns (specifically, carbon dioxide output) (Farb et al., 2013; Grant & Rainville, 2009; Zeidan et al., 2011), which in turn are likely to affect CBF effects in the brain; might these changes bias our neuroimaging measures of brain activity? While employing perfusion fMRI may not correct the effects of respiration changes on CBF during meditation, it can identify whether CBF changes are exhibited. Another possibility for evaluating this issue is to measure markers of respiration rate and amplitude (via a respiration belt), which can then be included as covariates or outcomes in mindfulness meditation imaging study analyses.

New imaging technologies offer new opportunities to build models of the *mindful brain*, which can help in the development of mindfulness-based treatments that specifically target a spectrum of health outcomes. Imaging methodologies such as real-time fMRI have already begun to contribute novel mechanistic insights into how mindfulness affects self-referential processing, social interactions, and attention (Garrison et al., 2013). Real-time fMRI allows us to record moment-to-moment neural information in conjunction with first-person accounts. This technique can provide ample opportunities for individuals to learn, via real-time neurofeedback, how to modulate health-related outcomes such as pain (deCharms et al., 2005), affective disorders (Johnston et al., 2011), and craving (Brewer et al., 2013) through mindfulness-based treatment approaches. Studies assessing changes in gene expression through epigenetic methodologies are also making an impact in delineating the benefits of meditation-based cognitive practices (Black et al., 2013; Creswell et al., 2012; Qu, Olafsrud, Meza-Zepeda, & Saatcioglu, 2013). While MRI scanner technology is improving rapidly, and the use of imaging techniques are becoming more common, assessing and integrating neural, endocrine, physiological, and behavioral data will continue to provide novel and clinically relevant insights into mindfulness-based improvements in health outcomes such as cancer, chronic pain, posttraumatic stress disorder, and substance dependency outcomes.

This chapter has offered an initial account of the neurobiology of mindfulness meditation, and the coming years offer many opportunities to extend our understanding in this area. We will no doubt be better able to gauge how mindfulness meditation practice affects the neurobiological mechanisms that mediate mental and physical health outcomes. Furthermore, identifying the neural substrates of mindfulness-based interventions will help tailor interventions to specific mental and physical health outcomes and thereby perhaps reduce health care costs and medication dependency (Blumenthal et al., 2002; Herman, Craig, & Caspi, 2005; Teasdale et al., 2000). Understanding the nature and structure of the mindful brain is thus a worthy pursuit that may also help to bring more clarity to the still enigmatic world of human consciousness.

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REFERENCES

Anand, A., Li, Y., Wang, Y., Wu, J., Gao, S., Bukhari, L., et al. (2005). Activity and connectivity of brain mood regulating circuit in depression: A functional magnetic resonance study. *Biological Psychiatry, 57*(10), 1079–1088.

Austin, J. H. (1998). *Zen and the brain: Toward an understanding of meditation and consciousness.* Cambridge, MA: MIT Press.

Baerentsen, K. B., Stodkilde-Jorgensen, H., Sommerlund, B., Hartmann, T., Damsgaard-Madsen, J., Fosnaes, M., et al. (2010). An investigation of brain processes supporting meditation. *Cognitive Processing, 11*(1), 57–84.

Banks, S. J., Eddy, K. T., Angstadt, M., Nathan, P. J., & Phan, K. L. (2007). Amygdala–frontal connectivity during emotion regulation. *Social Cognitive and Affective Neuroscience, 2*(4), 303–312.

Bishop, S. J. (2007). Neurocognitive mechanisms of anxiety: An integrative account. *Trends in Cognitive Sciences, 11*(7), 307–316.

Bishop, S. J. (2009). Trait anxiety and impoverished prefrontal control of attention. *Nature Neuroscience, 12*(1), 92–98.

Black, D. S., Cole, S. W., Irwin, M. R., Breen, E., St Cyr, N. M., Nazarian, N., et al. (2013). Yogic meditation reverses NF-κB and IRF-related transcriptome dynamics in leukocytes of family dementia caregivers in a randomized controlled trial. *Psychoneuroendocrinology, 38*(3), 348–355.

Blumenthal, J. A., Babyak, M., Wei, J., O'Connor, C., Waugh, R., Eisenstein, E., et al. (2002). Usefulness of psychosocial treatment of mental stress-induced myocardial ischemia in men. *American Journal of Cardiology, 89*(2), 164–168.

Brefczynski-Lewis, J. A., Lutz, A., Schaefer, H. S., Levinson, D. B., & Davidson, R. J. (2007). Neural correlates of attentional expertise in long-term meditation practitioners. *Proceedings of the National Academy of Sciences USA, 104*(27), 11483–11488.

Brewer, J. A., Elwafi, H. M., & Davis, J. H. (2013). Craving to quit: psychological models and neurobiological mechanisms of mindfulness training as treatment for addictions. *Psychology of Addictive Behaviors, 27*(2), 366–379.

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. *Proceedings of the National Academy of Sciences USA, 108*(50), 20254–20259.

Brown, C. A., & Jones, A. K. (2010). Meditation experience predicts less negative appraisal of pain: Electrophysiological evidence for the involvement of anticipatory neural responses. *Pain, 150*(3), 428–438.

Brown, K. W., Goodman, R. J., & Inzlicht, M. (2013). Dispositional mindfulness and the attenuation of neural responses to emotional stimuli. *Social Cognitive and Affective Neuroscience, 8*(1), 93–99.

Brown, K. W., & Ryan, R. M. (2003). The benefits of being present: Mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology, 84*(4), 822–848.

Brown, K. W., Weinstein, N., & Creswell, J. D. (2012). Trait mindfulness modulates neuroendocrine and affective responses to social evaluative threat. *Psychoneuroendocrinology, 37*(12), 2037–2041.

Buckner, R. L. (2012). The serendipitous discovery of the brain's default network. *NeuroImage, 62*(2), 1137–1145.

Cahn, B. R., Delorme, A., & Polich, J. (2013). Event-related delta, theta, alpha and gamma correlates to auditory oddball processing during Vipassanā meditation. *Social Cognitive and Affective Neuroscience, 8*(1), 100–111.

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

Cahn, B. R., & Polich, J. (2009). Meditation (Vipassanā) and the P3a event-related brain potential. *International Journal of Psychophysiology, 72*(1), 51–60.

Ciesla, J. A., Reilly, L. C., Dickson, K. S., Emanuel, A. S., & Updegraff, J. A. (2012). Dispositional mindfulness moderates the effects of stress among adolescents: Rumination as a mediator. *Journal of Clinical Child and Adolescent Psychology, 41*(6), 760–770.

Coghill, R. C., Gilron, I., & Iadarola, M. J. (2001). Hemispheric lateralization of somatosensory processing. *Journal of Neurophysiology, 85*(6), 2602–2612.

Cole, M. W., & Schneider, W. (2007). The cognitive control network: Integrated cortical regions with dissociable functions. *NeuroImage, 37*(1), 343–360.

Creswell, J. D., Irwin, M. R., Burklund, L. J., Lieberman, M. D., Arevalo, J. M., Ma, J., et al. (2012). Mindfulness-based stress reduction training reduces loneliness and pro-inflammatory gene expression in older adults: A small randomized controlled trial. *Brain, Behavior, and Immunity, 26*(7), 1095–1101.

Creswell, J. D., Way, B. M., Eisenberger, N. I., & Lieberman, M. D. (2007). Neural correlates of dispositional mindfulness during affect labeling. *Psychosomatic Medicine, 69*(6), 560–565.

Crick, F. (1984). Function of the thalamic reticular complex: The searchlight hypothesis. *Proceedings of the National Academy of Sciences USA, 81*(14), 4586–4590.

Critchley, H. D. (2004). The human cortex responds to an interoceptive challenge. *Proceedings of the National Academy of Sciences USA, 101*(17), 6333–6334.

Critchley, H. D., Mathias, C. J., Josephs, O., O'Doherty, J., Zanini, S., Dewar, B. K., et al. (2003). Human cingulate cortex and autonomic control: Converging neuroimaging and clinical evidence. *Brain, 126*(10), 2139–2152.

Critchley, H. D., Wiens, S., Rotshtein, P., Ohman, A., & Dolan, R. J. (2004). Neural systems supporting interoceptive awareness. *Nature Neuroscience, 7*(2), 189–195.

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

deCharms, R. C., Maeda, F., Glover, G. H., Ludlow, D., Pauly, J. M., Soneji, D., et al. (2005). Control over brain activation and pain learned by using real-time functional MRI. *Proceedings of the National Academy of Sciences USA, 102*(51), 18626–18631.

Drabant, E. M., McRae, K., Manuck, S. B., Hariri, A. R., & Gross, J. J. (2009). Individual differences in typical reappraisal use predict amygdala and prefrontal responses. *Biological Psychiatry, 65*(5), 367–373.

Dunne, J. (2011). Toward an understanding of non-dual mindfulness. *Contemporary Buddhism, 12*(1), 69–86.

Farb, N. A., Anderson, A. K., Mayberg, H., Bean, J., McKeon, D., & Segal, Z. V. (2010). Minding one's emotions: Mindfulness training alters the neural expression of sadness. *Emotion, 10*(1), 25–33.

Farb, N. A., Segal, Z. V., & Anderson, A. K. (2013). Mindfulness meditation training alters cortical representations of interoceptive attention. *Social Cognitive and Affective Neuroscience, 8*(1), 15–26.

Farb, N. A., Segal, Z. V., Mayberg, H., Bean, J., McKeon, D., Fatima, Z., et al. (2007). Attending to the present: mindfulness meditation reveals distinct neural modes of self-reference. *Social Cognitive and Affective Neuroscience, 2*(4), 313–322.

Fransson, P., & Marrelec, G. (2008). The precuneus/posterior cingulate cortex plays a pivotal role in the default mode network: Evidence from a partial correlation network analysis. *NeuroImage, 42*(3), 1178–1184.

Froeliger, B., Garland, E. L., Kozink, R. V., Modlin, L. A., Chen, N. K., McClernon, F. J., et al. (2012). Meditation-state functional connectivity (msFC): Strengthening of the dorsal attention network and beyond. *Evidence-Based Complementary and Alternative Medicine, 2012*, Art. No. 680407.

Gard, T., Holzel, B. K., Sack, A. T., Hempel, H., Vaitl, D., & Ott, U. (2011). Pain attenuation through mindfulness is associated with decreased cognitive control and increased sensory processing in the brain. *Cerebral Cortex, 191*(1), 36–43.

Garland, E., Gaylord, S., & Park, J. (2009). The role of mindfulness in positive reappraisal. *Explore (NY), 5*(1), 37–44.

Garland, E. L., Fredrickson, B., Kring, A. M., Johnson, D. P., Meyer, P. S., & Penn, D. L. (2010). Upward spirals of positive emotions counter downward spirals of negativity: Insights from the broaden-and-build theory and affective neuroscience on the treatment of emotion dysfunctions and deficits in psychopathology. *Clinical Psychology Review, 30*, 849–864.

Garland, E. L., & Roberts-Lewis, A. (2013). Differential roles of thought suppression and dispositional mindfulness in posttraumatic stress symptoms and craving. *Addictive Behaviors, 38*(2), 1555–1562.

Garrison, K. A., Santoyo, J. F., Davis, J. H., Thornhill, T. A., IV, Kerr, C. E., & Brewer, J. A. (2013). Effortless awareness: Using real time neurofeedback to investigate correlates of posterior cingulate cortex activity in meditators' self-report. *Frontiers in Human Neuroscience, 7*, 440.

Goldin, P., Ziv, M., Jazaieri, H., & Gross, J. J. (2012). Randomized controlled trial of mindfulness-based stress reduction versus aerobic exercise: Effects on the self-referential brain network in social anxiety disorder. *Frontiers in Human Neuroscience, 6*, 295.

Goldin, P., Ziv, M., Jazaieri, H., Hahn, K., & Gross, J. J. (2013). MBSR vs aerobic exercise in social anxiety: fMRI of emotion regulation of negative self-beliefs. *Social Cognitive and Affective Neuroscience, 8*(1), 65–72.

Goldin, P. R., & Gross, J. J. (2010). Effects of mindfulness-based stress reduction (MBSR) on emotion regulation in social anxiety disorder. *Emotion, 10*(1), 83–91.

Goldin, P. R., Manber-Ball, T., Werner, K., Heimberg, R., & Gross, J. J. (2009). Neural mechanisms of cognitive reappraisal of negative self-beliefs in social anxiety disorder. *Biological Psychiatry, 66*(12), 1091–1099.

Goldin, P. R., McRae, K., Ramel, W., & Gross, J. J. (2008). The neural bases of emotion regulation: reappraisal and suppression of negative emotion. *Biological Psychiatry, 63*(6), 577–586.

Grant, J. A., Courtemanche, J., Duerden, E. G., Duncan, G. H., & Rainville, P. (2010). Cortical thickness and pain sensitivity in zen meditators. *Emotion, 10*(1), 43–53.

Grant, J. A., Courtemanche, J., & Rainville, P. (2011). A non-elaborative mental stance and decoupling of executive and pain-related cortices predicts low pain sensitivity in Zen meditators. *Pain, 152*(1), 150–156.

Grant, J. A., & Rainville, P. (2009). Pain sensitivity and analgesic effects of mindful states in Zen meditators: A cross-sectional study. *Psychosomatic Medicine, 71*(1), 106–114.

Grossman, P., Niemann, L., Schmidt, S., & Walach, H. (2004). Mindfulness-based stress reduction and health benefits: A meta-analysis. *Journal of Psychosomatic Research, 57*(1), 35–43.

Gunaratana, H. (2002). *Mindfulness in plain English*. Boston: Wisdom.

Hasenkamp, W., & Barsalou, L. W. (2012). Effects of meditation experience on functional connectivity of distributed brain networks. *Frontiers in Human Neuroscience, 6*, 38.

He, B., Yang, L., Wilke, C., & Yuan, H. (2011). Electrophysiological imaging of brain activity and connectivity-challenges and opportunities. *IEEE Transactions on Biomedical Engineering, 58*(7), 1918–1931.

Herman, P. M., Craig, B. M., & Caspi, O. (2005). Is complementary and alternative medicine (CAM) cost-effective?: A systematic review. *BMC Complementary and Alternative Medicine, 5*, 11.

Hölzel, B. K., Carmody, J., Evans, K. C., Hoge, E. A., Dusek, J. A., Morgan, L., et al. (2010). Stress reduction correlates with structural changes in the amygdala. *Social Cognitive and Affective Neuroscience, 5*(1), 11–17.

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*, 537–559.

Hölzel, B. K., Ott, U., Gard, T., Hempel, H., Weygandt, M., Morgen, K., et al. (2008). Investigation of mindfulness meditation practitioners with voxel-based morphometry. *Social Cognitive and Affective Neuroscience, 3*(1), 55–61.

Hölzel, B. K., Ott, U., Hempel, H., Hackl, A., Wolf, K., Stark, R., et al. (2007). Differential engagement of anterior cingulate and adjacent medial frontal cortex in adept meditators and non-meditators. *Neuroscience Letters, 421*(1), 16–21.

Howseman, A. M., & Bowtell, R. W. (1999). Functional magnetic resonance imaging: imaging techniques and contrast mechanisms. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 354*(1387), 1179–1194.

Johnston, S., Linden, D. E., Healy, D., Goebel, R., Habes, I., & Boehm, S. G. (2011). Upregulation of emotion areas through neurofeedback with a focus on positive mood. *Cognitive, Affective and Behavioral Neuroscience, 11*(1), 44–51.

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

Kabat-Zinn, J., Lipworth, L., & Burney, R. (1985). The clinical use of mindfulness meditation for the self-regulation of chronic pain. *Journal of Behavioral Medicine, 8*(2), 163–190.

Killingsworth, M. A., & Gilbert, D. T. (2010). A wandering mind is an unhappy mind. *Science, 330*(6006), 932.

Kilpatrick, L. A., Suyenobu, B. Y., Smith, S. R., Bueller, J. A., Goodman, T., Creswell, J. D., et al. (2011). Impact of mindfulness-based stress reduction training on intrinsic brain connectivity. *NeuroImage, 56*(1), 290–298.

Konova, A. B., Moeller, S. J., Tomasi, D., Volkow, N. D., & Goldstein, R. Z. (2013). Effects of methylphenidate on resting-state functional connectivity of the mesocorticolimbic dopamine pathways in cocaine addiction. *JAMA Psychiatry, 70*(8), 857–868.

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (1997). *International Affective Picture System (IAPS): Technical manual and affective ratings*. Gainsville: University of Florida.

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., et al. (2005). Meditation experience is associated with increased cortical thickness. *NeuroReport, 16*(17), 1893–1897.

LeDoux, J. E. (2013). The slippery slope of fear. *Trends in Cognitive Sciences, 17*(4), 155–156.

Loggia, M. L., Kim, J., Gollub, R. L., Vangel, M. G., Kirsch, I., Kong, J., et al. (2013). Default mode network connectivity encodes clinical pain: An arterial spin labeling study. *Pain, 154*(1), 24–33.

Lutz, A., Greischar, L. L., Perlman, D. M., & Davidson, R. J. (2009). BOLD signal in insula is differentially related to cardiac function during compassion meditation in experts vs. novices. *NeuroImage, 47*(3), 1038–1046.

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 USA, 101*(46), 16369–16373.

Lutz, A., McFarlin, D. R., Perlman, D. M., Salomons, T. V., & Davidson, R. J. (2013). Altered anterior insula activation during anticipation and experience of painful stimuli in expert meditators. *NeuroImage, 64*, 538–546.

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

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.

Maclean, K. A., Ferrer, E., Aichele, S. R., Bridwell, D. A., Zanesco, A. P., Jacobs, T. L., et al. (2010). Intensive meditation training improves perceptual discrimination and sustained attention. *Psychological Science, 21*(6), 829–839.

Manna, A., Raffone, A., Perrucci, M. G., Nardo, D., Ferretti, A., Tartaro, A., et al. (2010). Neural correlates of focused attention and cognitive monitoring in meditation. *Brain Research Bulletin, 82*(1–2), 46–56.

Mirams, L., Poliakoff, E., Brown, R. J., & Lloyd, D. M. (2013). Brief body-scan meditation practice improves somatosensory perceptual decision making. *Consciousness and Cognition, 22*(1), 348–359.

Modinos, G., Ormel, J., & Aleman, A. (2010). Individual differences in dispositional mindfulness and brain activity involved in reappraisal of emotion. *Social Cognitive and Affective Neuroscience, 5*(4), 369–377.

Murphy, M. J., Mermelstein, L. C., Edwards, K. M., & Gidycz, C. A. (2012). The benefits of dispositional mindfulness in physical health: A longitudinal study of female college students. *Journal of American College Health, 60*(5), 341–348.

Nhât Hanh, T. (1987). *The miracle of mindfulness: A manual on meditation* (rev. ed.). Boston: Beacon Press.

O'Doherty, J., Kringelbach, M. L., Rolls, E. T., Hornak, J., & Andrews, C. (2001). Abstract reward and punishment representations in the human orbitofrontal cortex. *Nature Neuroscience, 4*(1), 95–102.

Ochsner, K. N., Ray, R. D., Cooper, J. C., Robertson, E. R., Chopra, S., Gabrieli, J. D., et al. (2004). For better or for worse: Neural systems supporting the cognitive down- and up-regulation of negative emotion. *NeuroImage, 23*(2), 483–499.

Pagnoni, G. (2012). Dynamical properties of BOLD activity from the ventral posteromedial cortex associated with meditation and attentional skills. *Journal of Neuroscience, 32*(15), 5242–5249.

Peters, J., & Buchel, C. (2010). Neural representations of subjective reward value. *Behavioural Brain Research, 213*(2), 135–141.

Qu, S., Olafsrud, S. M., Meza-Zepeda, L. A., & Saatcioglu, F. (2013). Rapid gene expression changes in peripheral blood lymphocytes upon practice of a comprehensive yoga program. *PloS ONE, 8*(4), e61910.

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences USA, 98*(2), 676–682.

Rolls, E. T., & Grabenhorst, F. (2008). The orbitofrontal cortex and beyond: From affect to decision-making. *Progress in Neurobiology, 86*(3), 216–244.

Saggar, M., King, B. G., Zanesco, A. P., Maclean, K. A., Aichele, S. R., Jacobs, T. L., et al. (2013). Intensive training induces longitudinal changes in meditation state-related EEG oscillatory activity. *Frontiers in Human Neuroscience, 6*, 256.

Scheeringa, R., Bastiaansen, M. C., Petersson, K. M., Oostenveld, R., Norris, D. G., & Hagoort, P. (2008). Frontal theta EEG activity correlates negatively with the default mode network in resting state. *International Journal of Psychophysiology, 67*(3), 242–251.

Schoenbaum, G., Takahashi, Y., Liu, T. L., & McDannald, M. A. (2011). Does the orbitofrontal cortex signal value? *Annals of the New York Academy of Sciences, 1239*, 87–99.

Shapiro, S. L., Carlson, L. E., Astin, J. A., & Freedman, B. (2006). Mechanisms of mindfulness. *Journal of Clinical Psychology, 62*(3), 373–386.

Sheline, Y. I., Price, J. L., Yan, Z., & Mintun, M. A. (2010). Resting-state functional MRI in depression unmasks increased connectivity between networks via the dorsal nexus. *Proceedings of the National Academy of Sciences USA, 107*(24), 11020–11025.

Short, B. E., Kose, S., Mu, Q., Borckardt, J., Newberg, A., George, M. S., et al. (2010). Regional brain activation during meditation shows time and practice effects: An exploratory FMRI study. *Evidence-Based Complementary and Alternative Medicine, 7*(1), 121–127.

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.

Smallwood, J., Fitzgerald, A., Miles, L. K., & Phillips, L. H. (2009). Shifting moods, wandering minds: Negative moods lead the mind to wander. *Emotion, 9*(2), 271–276.

Sutherland, M. T., McHugh, M. J., Pariyadath, V., & Stein, E. A. (2012). Resting state functional connectivity in addiction: Lessons learned and a road ahead. *NeuroImage, 62*(4), 2281–2295.

Tamagawa, R., Giese-Davis, J., Speca, M., Doll, R., Stephen, J., & Carlson, L. E. (2013). Trait mindfulness, repression, suppression, and self-reported mood and stress symptoms among women with breast cancer. *Journal of Clinical Psychology, 69*(3), 264–277.

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. *Proceedings of the National Academy of Sciences USA, 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. *Proceedings of the National Academy of Sciences USA, 104*(43), 17152–17156.

Tang, Y. Y., Tang, R., & Posner, M. I. (2013). Brief meditation training induces smoking reduction. *Proceedings of the National Academy of Sciences USA, 110*(34), 13971–13975.

Taren, A. A., Creswell, J. D., & Gianaros, P. J. (2013). Dispositional mindfulness co-varies with smaller amygdala and caudate volumes in community adults. *PloS One, 8*(5), e64574.

Taylor, V. A., Daneault, V., Grant, J., Scavone, G., Breton, E., Roffe-Vidal, S., et al. (2013). Impact of meditation training on the default mode network during a restful state. *Social Cognitive and Affective Neuroscience, 8*(1), 4–14.

Taylor, V. A., Grant, J., Daneault, V., Scavone, G., Breton, E., Roffe-Vidal, S., et al. (2011). Impact of mindfulness on the neural responses to emotional pictures in experienced and beginner meditators. *NeuroImage, 57*(4), 1524–1533.

Teasdale, J. D., Segal, Z. V., Williams, J. M., Ridgeway, V. A., Soulsby, J. M., & Lau, M. A. (2000). Prevention of relapse/recurrence in major depression by mindfulness-based cognitive therapy. *Journal of Consulting and Clinical Psychology, 68*(4), 615–623.

Urry, H. L., van Reekum, C. M., Johnstone, T., Kalin, N. H., Thurow, M. E., Schaefer, H. S., et al. (2006). Amygdala and ventromedial prefrontal cortex are inversely coupled during regulation of negative affect and predict the diurnal pattern of cortisol secretion among older adults. *Journal of Neuroscience, 26*(16), 4415–4425.

Vago, D. R., & Silbersweig, D. A. (2012). Self-awareness, self-regulation, and self-transcendence (S-ART): A framework for understanding the neurobiological mechanisms of mindfulness. *Frontiers in Human Neuroscience, 6*, 296.

Wager, T. D., Davidson, M. L., Hughes, B. L., Lindquist, M. A., & Ochsner, K. N. (2008). Prefrontal-subcortical pathways mediating successful emotion regulation. *Neuron, 59*(6), 1037–1050.

Wallace, B. A. (2006). *The Attention Revolution: Unlocking the power of the focused mind*. Somerville, MA: Wisdom.

Way, B. M., Creswell, J. D., Eisenberger, N. I., & Lieberman, M. D. (2010). Dispositional mindfulness and depressive symptomatology: Correlations with limbic and self-referential neural activity during rest. *Emotion, 10*(1), 12–24.

Westbrook, C., Creswell, J. D., Tabibnia, G., Julson, E., Kober, H., & Tindle, H. A. (2013). Mindful attention reduces neural and self-reported cue-induced craving in smokers. *Social Cognitive and Affective Neuroscience, 8*(1), 73–84.

Zeidan, F., Gordon, N. S., Merchant, J., & Goolkasian, P. (2010). The effects of brief mindfulness meditation training on experimentally induced pain. *Journal of Pain, 11*(3), 199–209.

Zeidan, F., Grant, J. A., Brown, C. A., McHaffie, J. G., & Coghill, R. C. (2012). Mindfulness meditation-related pain relief: evidence for unique brain mechanisms in the regulation of pain. *Neuroscience Letters, 520*(2), 165–173.

Zeidan, F., Johnson, S. K., Diamond, B. J., David, Z., & Goolkasian, P. (2010). Mindfulness meditation improves cognition: evidence of brief mental training. *Consciousness and Cognition, 19*(2), 597–605.

Zeidan, F., Johnson, S. K., Gordon, N. S., & Goolkasian, P. (2010). Effects of brief and sham mindfulness meditation on mood and cardiovascular variables. *Journal of Alternative and Complementary Medicine, 16*(8), 867–873.

Zeidan, F., Martucci, K. T., Kraft, R. A., Gordon, N. S., McHaffie, J. G., & Coghill, R. C. (2011). Brain mechanisms supporting the modulation of pain by mindfulness meditation. *Journal of Neuroscience, 31*(14), 5540–5548.

Zeidan, F., Martucci, K. T., Kraft, R. A., McHaffie, J. G., & Coghill, R. C. (2014). Neural correlates of mindfulness meditation-related anxiety relief. *Social Cognitive and Affective Neuroscience, 9*(6), 751–759.

Zeng, L. L., Shen, H., Liu, L., Wang, L., Li, B., Fang, P., et al. (2012). Identifying major depression using whole-brain functional connectivity: A multivariate pattern analysis. *Brain, 135*(5), 1498–1507.