

Neural mechanisms of mindfulness and meditation: Evidence from neuroimaging studies

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Abstract

Mindfulness is the dispassionate, moment-by-moment awareness of sensations, emotions and thoughts. Mindfulness-based interventions are being increasingly used for stress, psychological well being, coping with chronic illness as well as adjunctive treatments for psychiatric disorders. However, the neural mechanisms associated with mindfulness have not been well characterized. Recent functional and structural neuroimaging studies are beginning to provide insights into neural processes associated with the practice of mindfulness. A review of this literature revealed compelling evidence that mindfulness impacts the function of the medial cortex and associated default mode network as well as insula and amygdala. Additionally, mindfulness practice appears to effect lateral frontal regions and basal ganglia, at least in some cases. Structural imaging studies are consistent with these findings and also indicate changes in the hippocampus. While many questions remain unanswered, the current literature provides evidence of brain regions and networks relevant for understanding neural processes associated with mindfulness.

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Key words: Mindfulness; Meditation; Medial cortex, amygdala; Emotional control

Core tip: Mindfulness training is used for stress and as an adjunctive treatment for psychiatric disorders. Functional neuroimaging studies are beginning to provide insights into neural processes associated with the practice of mindfulness. These studies clearly indicate that the practice of mindfulness changes brain function in areas including the medial cortex, default mode network, insula, amygdala, lateral frontal regions and basal ganglia.

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INTRODUCTION

Mindfulness has been described as dispassionate, non-evaluative, and continuous moment-by-moment awareness of, sensations, perceptions, emotions and thoughts^[1]. A similar definition explains mindfulness as “the awareness that emerges through paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience moment by moment^[2].”

Mindfulness training involves meditation. Mindfulness meditation practice is the framework used to develop the state, or skill, of mindfulness. The word “meditation” stems from the Latin *meditari*, which means to participate in contemplation or deliberation. Meditation includes a variety of practices aimed at focusing attention and awareness. Two general forms of meditation exist. These are focused attention and open monitoring^[3]. Initially a

practitioner will often utilize focused attention practice to enhance attentional skills^[4]. Then, it will be possible to engage in open monitoring, which involves moment-by-moment awareness of whatever occurs in one's awareness^[4].

Mindfulness originated in Buddhist spiritual practices. However, secular, group therapy approaches utilizing manuals and standardized methods have been developed for clinical use. Two of these are Mindfulness-Based Stress Reduction (MBSR) and Mindfulness-Based Cognitive Therapy (MBCT). As reviewed elsewhere^[5], there has been increased interest in mindfulness and meditation in recent years. In particular, there has been increased use of the secular mindfulness-based interventions for stress, coping with physical illness and as adjunctive treatments for psychiatric disorders^[5].

This manuscript reviews recent neuroimaging studies that enhance our understanding of the neural mechanisms of mindfulness.

SEARCH

Several PubMed searches were conducted with terms mindfulness and neuroimaging, mindfulness and fMRI, mindfulness and MRI and mindfulness and mechanisms, meditation and neuroimaging, meditation and fMRI and mediation and MRI. These initial searches resulted in the review of 248 abstracts. Those most relevant for understanding neural mechanisms of mindfulness are included herein.

STUDIES OF NEUROBIOLOGICAL MECHANISMS OF MINDFULNESS AND MEDITATION

A relatively large number of functional neuroimaging studies now enhance our understanding of the neural processes associated with mindfulness. A smaller number of structural imaging studies have been conducted as well.

FUNCTIONAL IMAGING STUDIES

The review focused on recent functional imaging studies that enhance our understanding of neural processes associated with the practice of mindfulness meditation. Results are summarized in detail in Table 1.

Many investigations studied individuals who had completed mindfulness training^[6-19]. A relatively large number studied experienced meditators^[20-33]. Additionally, some studies focused on brief mindfulness training^[34,35], state^[36] and trait^[37-39] mindfulness. One study compared expert and novice meditators^[40]. Finally some investigation focused on using mindfulness interventions for social anxiety disorder (SAD)^[8,13,15], generalized anxiety disorder (GAD)^[16] and bipolar disorder^[17].

STRUCTURAL IMAGING STUDIES

A growing body of literature indicates that mindfulness is associated with changes in brain structure. While this review focused on functional imaging a number of structural imaging studies were reviewed as well. These findings are summarized in Table 2. Studies reviewed used magnetic resonance imaging (MRI) to investigate brain morphometry^[19,41-50] as well as fractional anisotropy (FA)^[51,52] and gyrification^[53].

DISCUSSION

Though many questions remain unanswered, there is now a body of literature that provides important insights into the neural mechanisms associated with mindfulness. This evidence indicates brain regions that may be generally associated with mindfulness. More importantly, it is now possible to begin to understand neural processes that underlie the cognitive and emotional benefits of a mindfulness practice.

BRAIN REGIONS ASSOCIATED WITH MECHANISMS OF MINDFULNESS

The functional imaging studies reviewed herein indicate that mindfulness is associated with neural mechanisms involving multiple brain regions (Table 3). It is difficult to draw firm conclusions given the variability of methods utilized and diversity of the populations studied. Nonetheless, there is convincing evidence that mindfulness is associated with brain activation and/or connectivity of several regions as outlined in Table 3. Multiple studies implicate mechanisms involving frontal regions^[6,10,11,14,16-18,20,25,28,32-36,39]. A few studies implicate lateral regions^[11,16,25] including ventrolateral prefrontal cortex (VLPFC)^[16] and dorsolateral prefrontal cortex (DLPFC)^[11]. However, the strongest evidence is for medial frontal regions^[6,10,13,14,17,18,20,25,27,28,33,36] including anterior cingulate cortex (ACC)^[10,18,20,25,36]. Posterior medial regions are also involved^[13,22,29-31,33,36,37] primarily in the area of the posterior cingulate cortex (PCC) and precuneus^[13,22,30,31,33,36,37]. Thus, there is very strong evidence that anterior and posterior cortical midline structures (CMS) play a key role in the mechanisms of mindfulness^[6,10,13,14,17,18,20,25,27-33,36,37]. Since the CMS are key components of the default mode network (DMN), this circuitry is clearly implicated and a number of investigations have specifically focused on the role of the DMN^[21,24,26,30,33,37]. In addition, there is strong evidence for involvement of the insula^[6,10,14,18,23,25,32,35,38] and amygdala^[8,12,16,24,32,35,39]. A few studies also suggest involvement of the basal ganglia^[22,28] and thalamus^[10].

Structural imaging investigations (Table 2) provide strong evidence of mindfulness-related changes in the hippocampus^[19,41,45-49]. Other results are consistent with functional imaging studies and implicate CMS/DMN^[42,48,51], insula^[49,53], amygdala^[43-45], basal ganglia^[44,45,50] and thalamus^[45].

Table 1 Functional imaging studies of mindfulness and meditation

Ref.	Mindfulness intervention or condition	Result
Allen <i>et al</i> ^[11] Baerentsen <i>et al</i> ^[122]	Mindfulness Meditators	Diminished Stroop conflict and greater DLPFC responses during executive processing. At onset of meditation, activations occurred bilaterally in putamen and supplementary motor cortex with deactivations in the precuneus, the posterior cingulate cortex and the parieto-temporal area. With sustained meditation, activations were found in the caudate and deactivations were in right hemisphere white matter.
Brefczynski-Lewis <i>et al</i> ^[40]	Experienced meditators	Activation during sustained attention showed an inverted curve. Expert meditators (average 19000 h) of practice had more activation than novices but experts (average 44000 h) had less activation. In response to distracter sounds, expert meditators had less brain activation in areas associated with discursive thoughts and emotions but more activation in regions related to response inhibition and attention compared to novices.
Creswell <i>et al</i> ^[39]	Dispositional mindfulness	Dispositional mindfulness was associated with widespread prefrontal cortical activation, and decreased bilateral amygdala activity during affect labeling. Negative associations were found between prefrontal cortex and right amygdala responses in participants high in mindfulness.
Desbordes <i>et al</i> ^[12] Dickenson <i>et al</i> ^[34]	Mindfulness training Brief mindfulness induction	Decreased right amygdala activation in response to positive images. Focused breathing activated a parietal and prefrontal attention network and trait-level mindfulness correlated with parietal activation.
Farb <i>et al</i> ^[6]	MBSR	Interoceptive attention predicted greater activity in anterior insula but decreased recruitment of the DMPFC as well as altered functional connectivity between the DMPFC and the insula.
Farb <i>et al</i> ^[7]	Mindfulness training	Experiential focus resulted in reductions in cortical midline regions associated with narrative focus in novices. In trained participants, experiential focus was associated with reductions in the mPFC and increased engagement the lateral PFC, insula and somatosensory area. Analyses of functional connectivity revealed coupling between the insula and the mPFC in novices that was uncoupled in the mindfulness group.
Farb <i>et al</i> ^[14]	Mindfulness training	Participants had right-lateralized recruitment, including visceral and somatosensory areas associated with body sensation.
Gard <i>et al</i> ^[25]	Healthy meditators	Mindfulness practitioners experienced reduced unpleasantness of pain, which was associated with decreased activation in the lateral PFC and increased activation in the right insula. Anticipation of pain was associated with increased anterior cingulate cortex activation.
Garrison <i>et al</i> ^[30]	Healthy meditators	"Undistracted awareness" was associated with PCC deactivation. In contrast, "distracted awareness" corresponded with PCC activation.
Garrison <i>et al</i> ^[31] Goldin <i>et al</i> ^[8]	Healthy meditators MBSR for social anxiety disorder	Volitional decrease of the feedback graph was associated with deactivation of the PCC. MBSR yielded greater reductions in negative emotion and increased activation in attention-related parietal cortex compared to aerobic exercise.
Goldin <i>et al</i> ^[13]	MBSR for social anxiety disorder	MBSR led to increased activation in the PCC during negative self-view condition. DMPFC activation increases during negative self-view were associated with decreased disability and enhanced mindfulness.
Goldin <i>et al</i> ^[15]	MBSR for social anxiety disorder	MBSR associated with decreased anxiety and depression symptoms and improved self-esteem. Breath-focused attention task associated with decreased negative emotion and reduced amygdala activation.
Hasenkamp <i>et al</i> ^[26]	Healthy meditators	Brain activation in DMN during mind wandering, and in salience network regions during awareness of mind wandering.
Hasenkamp <i>et al</i> ^[27]	Healthy meditators	Meditation experience was associated with increased connectivity within attention networks and between regions involved with attention and medial frontal cortex.
Hölzel <i>et al</i> ^[16]	MBSR for GAD	Amygdala activation in response to neutral faces decreased, VLPFC activation increased and functional connectivity between amygdala and PFC increased. Changes in VLPFC activation and amygdala-PFC connectivity correlated with changes in Beck Anxiety Inventory scores.
Hölzel <i>et al</i> ^[20] Ives-Deliperi <i>et al</i> ^[17]	Vipassana meditators MBCT for bipolar disorder	Meditation associated with increased activation in ACC and dorsal medial prefrontal cortex. Activation increased in the medial PFC and posterior parietal lobe, in response to a mindfulness task. There was a correlation between activation changes in medial PFC and increased mindfulness.
Ives-Deliperi <i>et al</i> ^[36]	State mindfulness	Decreased activation in anterior insula, ACC, medial prefrontal cortex and bilateral precuneus during mindfulness meditation.
Kilpatrick <i>et al</i> ^[9]	MBSR	Increased functional connectivity of auditory and visual networks as well as between auditory cortex and areas associated with attention and self-referential processes. Enhanced anticorrelation between auditory and visual cortex as well as between visual cortex and attention and self-referential processing areas.
Kirk <i>et al</i> ^[23]	Experienced meditators	During the Ultimatum Game, controls recruit the anterior insula during unfair offers. In contrast, meditators display attenuated activity in high-level emotional representations of the anterior insula and increased activity in the low-level interoceptive representations of the posterior insula.
Kozasa <i>et al</i> ^[28]	Healthy meditators	Meditators had decreased activity relative to non-meditators in medial frontal, temporal, precentral, postcentral and basal ganglia regions during the incongruent conditions of the Stroop task.

Lutz <i>et al</i> ^[32]	Healthy subjects	Mindfulness increased activations in prefrontal regions during expectation of negative pictures. During perception of negative stimuli, reduced activation was found in amygdala and parahippocampal regions. Prefrontal and insular activations when expecting negative pictures correlated negatively with trait mindfulness.
Lutz <i>et al</i> ^[35]	Experienced meditators	Enhanced activity in the anterior insula and the mid-cingulate was associated with decreased pain-related unpleasantness.
Pagnoni <i>et al</i> ^[21]	Experienced meditators	vPMC activity was lower in meditators and was correlated with performance on a test for sustained attention. Functional connectivity analysis with a vPMC seed revealed attention performance was associated with the degree of temporal correlation between vPMC and the temporoparietal junction.
Pagnoni <i>et al</i> ^[29]	Zen meditators	Practitioners displayed reduced duration of the neural response linked to conceptual processing in regions of the DMN.
Paul <i>et al</i> ^[38]	Healthy subjects	Non-reactivity was inversely correlated with insula activation during inhibition to negative stimuli.
Shaurya Prakash <i>et al</i> ^[37]	Mindfulness disposition	Mindfulness disposition was associated with greater connectivity of the DMN, particularly in the PCC and the precuneus.
Taylor <i>et al</i> ^[24]	Experienced and beginning meditators	Experienced meditators had weaker functional connectivity between DMN regions.
Taylor <i>et al</i> ^[33]	Experienced and beginning meditators	Mindfulness attenuated emotional intensity. For experienced meditators, mindfulness induced a deactivation of DMN areas. For beginners, mindfulness induced a down-regulation of the left amygdala.
Wells <i>et al</i> ^[19]	MBSR	Increased functional connectivity between the PCC and medial prefrontal cortex and left hippocampus.
Baerentsen <i>et al</i> ^[22]	Mindfulness training	Reduced smoking craving associated with reduced activation of ACC. Mindful attention reduced functional connectivity between ACC and other craving-related regions.
Zeidan <i>et al</i> ^[10]	Mindfulness training	Anxiety relief associated with activation of the PFC and insula.
Zeidan <i>et al</i> ^[18]	Mindfulness training	Meditation decreased pain-associated activation of the contralateral somatosensory cortex. Reductions in pain were associated with increased activity in the ACC and insula. Decreased pain unpleasantness was associated with orbitofrontal activation and thalamic deactivation.

ACC: Anterior cingulate cortex; DMN: Default mode network; PCC: Posterior cingulate cortex; DMPFC: Dorsomedial prefrontal cortex; mPFC: Medial prefrontal cortex; vLPFC: Ventrolateral prefrontal cortex; vPMC: Ventral posterior medial cortex.

Table 2 Brain regions where structural imaging studies have demonstrated mindfulness related changes

Anterior cingulate cortex ^[42,51]
Orbitofrontal cortex ^[41]
Inferior temporal gyrus ^[49]
Insula ^[49,53]
Lingual gyrus ^[45]
Cuneus ^[45]
Sensorimotor cortex ^[42,53]
Fusiform gyrus ^[53]
Cuneus ^[53]
Corpus callosum ^[52]
Posterior cingulate cortex ^[48]
Cerebellum ^[48]
Hippocampus ^[19,41,45-49]
Amygdala ^[43-45]
Putamen ^[50]
Caudate ^[44,45]
Thalamus ^[45]

Taken together, these studies provide convincing evidence that neural mindfulness mechanisms involve the CMS/DMN, insula, hippocampus and amygdala. There is also evidence implicating lateral prefrontal regions, basal ganglia and thalamus.

NEURAL MECHANISMS OF THE COGNITIVE AND EMOTIONAL BENEFITS OF MINDFULNESS

As reviewed elsewhere^[5], the literature indicates that

mindfulness impacts attention, emotional regulation and thinking patterns. The following sections review evidence suggesting neural mechanisms underlying these effects.

ATTENTION

The development of attentional skills is the central component of mindfulness meditation practice^[3,4,54]. Training of attention skills enhances the capability to sustain non-judgmental awareness of one's thinking patterns, emotions, and sensory perceptions^[4,55]. This awareness facilitates gain distance from thoughts and emotions such that these become less powerful and compelling. In particular, mindfulness supports the recognition of automatic thinking patterns (discussed below).

Three neural networks, the alerting, orienting and executive, are thought to play specific roles in the attention process^[56,57]. The alerting network modulates task-specific alertness and attentional engagement and involves right frontal cortex, including DLPFC and ACC, as well as right parietal cortex^[57]. The orienting network controls stimulus selection, which is the capability to select precise information from numerous sensory stimuli. This network includes the frontal eye fields, superior parietal cortex, superior colliculus and temporal parietal junction^[57]. Finally, the executive control circuitry mediates control of attention. This function includes top-down control as well as monitoring and resolution of conflict between computations involving planning or decision-making, error detection and regulation of thoughts and feelings^[57]. In regard to brain regions involve, the ACC, lateral frontal

Table 3 Brain regions involved with mindfulness mechanisms

Frontal cortex ^[6,10,11,14,16-18,20,25,28,32-36,39]
Lateral frontal cortex ^[11,16,25]
Ventrolateral prefrontal cortex ^[16]
Dorsolateral prefrontal cortex ^[11]
Medial frontal cortex ^[6,10,13,14,17,18,20,25,27,28,33,36]
Anterior cingulate cortex ^[10,18,20,25,36]
Orbitofrontal cortex ^[10]
Posterior medial cortex ^[13,22,29-31,33,36,37]
Posterior cingulate cortex/precuneus ^[13,22,30,31,33,36,37]
Ventral posteromedial cortex ^[29]
Insula ^[6,10,14,18,23,25,32,35,38]
Temporal cortex ^[28,33]
Temporoparietal junction ^[29]
Sensorimotor cortex ^[6,10,28]
Inferior parietal lobule ^[6,33]
Parahippocampal gyrus ^[35]
Amygdala ^[8,12,16,24,32,35,39]
Basal ganglia ^[22,28]
Thalamus ^[10]

cortex, and basal ganglia contribute to executive control processes^[56].

Several studies suggest neural mechanisms associated with mindfulness-related improvements in attention. An MBSR study examined the neural processes of deploying attention to control responses to negative beliefs about self in social anxiety disorder^[15]. MBSR yielded decreased negative emotion and increased activation in attention modulating parietal regions. In a study to investigate meta-awareness and regulation of mind wandering and related influence on DMN activity, investigators collected fMRI data from a group of Zen meditators and a meditation-naïve control group engaging in an attention-to-breathing task^[29]. Results indicated the incidence of states of elevated ventral posterior medial cortex (vPMC) activity was lower in meditators and was significantly correlated with performance on a test for sustained attention. Analysis of functional connectivity using the vPMC seed revealed an association between attention performance and the degree of temporal correlation between right temporoparietal junction (TPJ) and vPMC. Another study aimed to evaluate the performance of meditators and non-meditators during an fMRI adapted Stroop Task, which requires impulse and attention control^[28]. Non-meditators showed increased activity compared to meditators in the middle temporal, medial frontal, pre and postcentral gyri and basal ganglia during the incongruent conditions. The authors conclude that their results suggest that meditation improves efficiency, perhaps by enhancing the ability to sustain attention and control impulses^[28]. A study examined a model^[26] that proposes four cognitive cycle intervals relevant for meditation: mind wandering, awareness of the wandering of one's mind, varying of attention, and prolonged attention. Fourteen meditators executed breath-focused meditation during scanning^[26]. Study participants were instructed to press a button when they realized their mind had wandered and then return their focus to the breath. Analyses of results indicated brain activity in regions associated with the

default mode during mind wandering, and in the salience network during awareness of mind wandering. Finally the executive network was active when shifting and sustaining attention.

Taken together, these investigation suggest that enhanced attention is associated with neural mechanisms involving attention-related parietal cortical regions^[15], vPMC^[29], TPJ^[29], CMS^[28], temporal cortex^[28], sensorimotor cortex^[28] and basal ganglia^[28]. Thus, mindfulness likely impacts all of the three attention networks.

In addition to training general attention processes, mindfulness facilitates the enhancement of interoceptive attention (IA) to visceral bodily sensations as they occur in the present moment. An fMRI study examined functional plasticity in accessing interoceptive representations in MBSR trained individuals^[14]. Mindfulness training predicted enhanced activity in anterior insula and diminished recruitment of dorsomedial prefrontal cortex (DMPFC) during IA, as well as changed functional connectivity between the DMPFC and insula.

In summary, mindfulness training appears to modify neural processes in the three attention networks and insula, which result in improved general and interoceptive attention respectively.

AUTOMATIC THOUGHTS AND SELF-REFERENTIAL THINKING

Cognitive neuroscience suggests two general types of mental processes, those that are controlled and those that are automatic. Automatic processes may be innately automatic or become automated as a result of learning and practice. Automated thoughts are initiated unconsciously and are not easy to interrupt or prevent^[57]. For example, when attention involuntarily drifts away from an object of conscious attention, the DMN and automatic thinking is engaged as an involuntary process^[58]. Objective awareness of automatic thoughts is understood to be a primary mechanism by which mindfulness decreases symptoms of depression, anxiety and stress^[5]. Objective awareness allows one to interpret thoughts as “just thoughts” and prevents experiencing irrational negative thinking as fact.

There is compelling evidence that mindfulness impacts DMN neural processes^[21,24,26,30,33,37]. Modification of this network likely plays a significant role in the objectification of the experience of automatic thoughts.

Most of the medial cortex acts as a functional unit known as the CMS^[59]. The CMS are part of the DMN^[60,61] and play a key role in stimulus independent thought (SIT)^[58,62]. Decreased activation of the CMS is correlated with decreased SIT^[63]. Therefore, the CMS may be the specific portion of the DMN involved with mindfulness-induced modification of automatic thinking.

As reviewed elsewhere^[5], self-referential thinking is a type of automatic cognitions particularly relevant for mood and anxiety disorders. The CMS are involved in self-referential thinking^[59,62,64]. A study of MBSR for Social anxiety disorder (SAD)^[13] used a self-referential en-

coding paradigm, which was administered at baseline and post-intervention in order to examine changes in neural and behavioral responses during fMRI. MBSR produced reductions in negative, as well as increases in positive views of self. MBSR led to increased brain responses in the PCC during the negative self-view. MBSR-related increased DMPFC activity during negative self-view was correlated with diminished social anxiety and augmented mindfulness. These findings suggest that mindfulness specifically attenuates maladaptive habitual self-views – at least in part - by impacting DMN regions and in particular the CMS.

EMOTIONAL REGULATION

A number of studies provide evidence of how mindfulness may contribute to enhanced emotional regulation. An fMRI study compared neural reactivity to provocation of sadness in participants completing 8 wk of mindfulness training (MT) and controls^[7]. Sadness caused activation of regions associated with self-referential thinking in the CMS. MT participants had a distinct activation pattern, with enhanced right hemisphere recruitment, including areas associated with body sensation. Another fMRI study examined effects of a short mindfulness intervention during the cued expectation and perception of pictures that were negative or potentially negative^[35]. The mindfulness intervention was correlated with increased activation of prefrontal cortex during the expectation of negative pictures. Perception of negative stimuli was associated with reduced activation in amygdala and parahippocampal gyrus. A study of MBCT for bipolar disorder using fMRI^[17] revealed improvements in the treatment group in measures of mindfulness, anxiety, affect regulation working memory, spatial memory and verbal fluency. Blood-oxygen level-dependent (BOLD) signal increases occurred in the medial prefrontal cortex (PFC) and parietal lobe. Analysis also revealed a correlation between signal changes in medial PFC and increased mindfulness. A study of MBSR for GAD^[16] found changes in amygdala and VLPFC activation as well as increased functional connectivity between amygdala and PFC regions comparing pre- to post-intervention. VLPFC activation and amygdala-prefrontal connectivity changes were correlated with change in Beck Anxiety Inventory scores. Another study of the longitudinal effects of meditation training on amygdala responses examined how 8 wk of meditation training impacts amygdala responses to emotional when in a non-meditative state^[12]. Adults with no prior meditation experience took part in Mindful Attention Training, Cognitively-Based Compassion Training or a control intervention. Participants underwent an fMRI experiment pre and post-intervention. In the scanner, they were presented images with positive, negative, and neutral emotional valences while remaining in a non-meditative state. Findings indicated decreased right amygdala activation in the Mindful Attention group in response to im-

ages of all valences. Another fMRI study explored the effects of mindfulness on the neural responses to emotional stimuli^[24]. Experienced and novice meditators were scanned as they viewed negative, positive, and neutral pictures in both a mindful state and non-mindful state. The mindful condition attenuated emotional intensity and imaging data indicated that this effect was achieved through distinct neural mechanisms for each group. For the experienced cohort, mindfulness produced deactivation of DMN areas but did not influence responses in brain regions involved in emotional reactivity. For beginners, mindfulness down-regulated the left amygdala during emotional processing. The authors conclude that the long-term practice of mindfulness leads to reduced emotional reactivity by promoting tolerance of emotion and enhanced present-moment awareness. A study investigated MBSR-induced changes in of emotional reactivity and regulation of negative beliefs about self in subjects with seasonal affective disorder (SAD)^[8]. Sixteen patients were scanned while reacting to negative beliefs and while regulating negative emotions. MBSR resulted in improved anxiety and depressive symptoms and self-esteem and during a breath-focused attention task. Subjects also showed diminished negative emotion and amygdala activity as well as increased activity in brain regions involved in attentional deployment.

These investigations indicate that mindfulness enhancement of emotional regulation appears involve modification of processing in lateral frontal regions^[16] CMS/DMN^[7,17,24], regions involved with IA^[7] and amygdala^[8,12,16,24,35]. Interestingly, there is evidence that these mechanisms may change based upon amount of meditation experience^[24]. The CMS are of particular interest in emotional regulation as these regions play a role in emotional processing^[65,66] including mediating the experience of sadness^[7]. Thus, these areas may represent a key link between self-referential thinking and emotional dysregulation in affective disorders.

CONCLUSION

The studies reviewed herein increase our understanding of the neural processes associated with mindfulness. A limitation of the literature is the fact that multiple methodologies have been utilized and a diverse population studied. Thus direct comparison of studies is not feasible. Nonetheless, the current literature begins to define the neural mechanisms of mindfulness and provides the groundwork for future investigations.

This review of this literature revealed compelling evidence that mindfulness impacts the function of the medial cortex and associated default mode network as well as insula and amygdala. Additionally, mindfulness practice appears to effect lateral frontal regions and basal ganglia, at least in some cases. Structural imaging studies are consistent with these findings and also indicate changes in the hippocampus.

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