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Literature Review

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Neural Correlates of Meditation: A Literature Review

Abstract

Meditation is consistently shown to effectively aid in the management of a number of biological and psychological problems. [1,2,3,4] Additionally, the regular practice of meditation can cultivate neurological dispositions which are oriented toward enhancing attentional processing mechanisms, a more recent discovery demonstrated through the application of functional imaging to meditation research. Research has confirmed that the human brain is capable and actively engaged in employing useful levels of plasticity throughout life as a result of learning and training processes.□ In this review of the literature, the body of research presently available on the neural correlates of meditation is examined and discussed, and the various central nervous system participants involved in the practice of the two categories of meditation, mindfulness and concentrative, are examined. Also discussed is the most recent discovery in meditation studies, cortical thickening elicited by meditation training.

Introduction

Since the 1970s, western researchers have been developing a working model of meditation as both a concerted application of inherent attentional processing mechanisms and a behavioral intervention capable of producing powerful physiological alterations, which include beneficial and potentially therapeutic outcomes. □ Meditation is a general term that refers to a myriad of mentation techniques whose methods and goals vary depending on the tradition from which they emerge. For the purpose of this review, meditation will be divided in to two categories: mindfulness and concentrative.[7] Lutz *et al.* have also termed these categories "open monitoring" (OM) and "focused attention" (FA) respectively.[8] While concentrative meditation techniques are more easily operationally defined due to their single or narrow attentional focus, mindfulness proves more challenging due to its "nondiscriminatory" mode of awareness. As noted by Ivanovski and Malhi in their review article, *The Psychological and Neurophysiological Concomitants of Mindfulness Forms of Meditation*:

> Mindfulness is a multifaceted construct that has proved difficult to operationalize, enveloping concepts that include nonjudgement, acceptance, present awareness, attention and intention. These 'components' are required to be present in order to experience mindfulness and it has been said that mindfulness is an activity that can be *described* using words but that cannot be wholly captured by words as it is a subtle process that invokes nonverbal experiences.[9] (77-78)

Lutz *et al.* have pointed out that in addition to a scant body of statistical evidence, the difficult dynamic between control populations and proper meditation training, and the sometimes large variations in meditation practitioner training backgrounds, a major problem for meditation research remains the need for a suitable operational definition. This is especially true of mindfulness meditation.

An operational definition of mindfulness, despite its elusiveness, is possible. Perhaps the most important figure in introducing the efficacy of a secularized and systematic version of mindfulness meditation to western medicine is John Kabat-Zinn, PhD, who defines mindfulness as intentionally paying attention to one's own thoughts, feelings and judgments.[10] Hayes and Feldman support the operational definition of mindfulness proposed by Bishop *et al.* [11]

Mindfulness, as operationally defined by Bishop *et al.* in *Mindfulness: A Proposed Operational Definition*, consists of a two-component model:

> The first component involves the self-regulation of attention so that it is maintained on immediate experience, thereby allowing for increased recognition of mental events in the present moment. The second component involves adopting a particular orientation toward one's experiences in the present moment, an orientation that is characterized by curiosity, openness, and acceptance. [12] (232)

Mindfulness meditation is becoming a widely appreciated in the scientific and healthcare communities as the preferred meditation approach for behavioral and cognitive interventions. [13-15] Ivanovski and Malhi note that while meditation has been studied in Western science since the 1970s, the majority of studies evaluated the positive physiological effects of Transcendental Meditation (TM), a form of concentrative mediation. More recently, focus has shifted towards mindfulness, likely due to the popularity and success of Kabat-Zinn's Mindfulness-Based Stress Reduction (MBSR) program, which was developed in 1979 through an outpatient stress reduction clinic at the University of Massachusetts Medical Center. [16] Mindfulness practices have drawn much attention from behavioral medicine and psychiatric fields, contributing to the formulation of various mindfulness interventions such as Kabat-Zinn's MBSR program. Another reason for the preference of mindfulness meditation over concentrative meditation is its historical roots in Buddhism, an increasingly popular worldview particularly among the educated elites in psychiatric and behavioral medicine fields. Practitioners of the Buddhist tradition are concerned with analyzing and defining the activities and applications of mindfulness meditation, and understanding the causal context from which meditation and, subsequently, mindfulness is made meaningful. [17,18]

Despite potential challenges in the development and application of an operational definition of mindfulness, successful mindfulness measurements have been developed. One of the most popular and proven methods of evaluating mindfulness is the Mindful Attention and Awareness Scale (MAAS). Similar evaluations of mindfulness include the Freiburg Mindfulness Inventory (FMI), the Kentucky Inventory of Mindfulness Skills (KIMS), the Cognitive and Affective Mindfulness Scale (CAMS), and the Mindfulness Questionnaire (MQ). In general, the subjective nature of self-report is a concern when evaluating levels of mindfulness in research. This question of the psychometric soundness of mindfulness questionnaires was examined by Baer *et al.*.[19] Researchers gave the above five mentioned mindfulness scores to 613 undergraduate students to evaluate the validity of the questionnaires. Psychological assessments were employed and compared, and statistical analysis was applied to the mindfulness scores to account for any psychological considerations in the participants. The following psychological assessments were utilized: Brief Symptom Inventory (BSI), NEO-Five Factor Inventory (NEO-FFI), Trait Meta-Mood Scale (TMMS), White Bear Suppression Inventory (WBSI), Difficulties in Emotion Regulation Scale (DERS), Toronto Alexithymia Scale (TAS-20), Scale of Dissociative Activities (SODAS), Acceptance and Action Questionnaire (AAQ), Cognitive Failures Questionnaire (CFQ), and the Self-Compassion Scale (SCS). The intercorrelations among mindfulness questionnaires indicated good internal consistency, and the authors suggest that the five evaluated mindfulness questionnaires successfully predict indicated correlations, and are useful predictors of mindfulness. Baer *et al.* state that the more popular MAAS has been shown to be positively correlated with openness to experience, emotional intelligence, and well-being, while negatively correlated with rumination ("wandering" or "unfocused" thoughts) and social anxiety. Additionally, higher scores on the MAAS have been shown to be positively correlated with one's level of mindfulness training. Such results support the use of mindfulness self-report assessments, and give confidence to researchers who aim to apply a useful operational definition of mindfulness meditation.

As a practice that aims to introduce nonjudgmental awareness into one's life, mindfulness meditation is potent in its potential offerings to cognitive and behavioral medicine fields.[20] While the study and utility of mindfulness meditation techniques, particularly MBSR, are fast becoming known as effective approaches to non-invasive behavioral intervention, the research is still in its infancy. Emerging from the Buddhist tradition, mindfulness is more accessible today than ever before and is for many westerners now an appreciable practice, through traditional venues in Buddhism and secular/psychological approaches like MBSR. Kabat-Zinn writes of the "inherentness" of mindfulness to the human experience.[16] However, the ability for a person to employ mindfulness is deeply dependent on their *consistent practice* ("training") of mindfulness meditation techniques, a reality that has made potential research subjects more difficult to find for comprehensive evaluation. Within the past decade, a greater number of people have begun practicing mindfulness regularly, making the job of the meditation researcher easier; this is reflected in the recent increases in mindfulness meditation studies, particularly those concerning functional imaging studies. In order to detect functional and, more recently, *structural* alterations using functional magnetic imaging (fMRI) and magnetic resonance imaging (MRI) respectively, for example, the mindfulness meditation practitioner would have to be sufficiently developed in the area of mindfulness practice, through long-term practice or sufficient and systematic exposure like that found in MBSR. This review will cover the exciting results and conclusions of the latest studies on mindfulness meditation, including functional imaging techniques, to paint a picture of the information currently available from such studies.

The cultivation of mindfulness through meditative practice leads to an increased sense of calmness and general well-being among practitioners, and is therefore seen as an important tool for clinicians and healthcare providers.[21] The demonstrable validity of mindfulness as a positive healthcare intervention are numerous, and includes an increase in immune function as demonstrated through a significant rise in antibody titers following flu vaccination, skin clearing in moderate to severe psoriasis as documented by clinical photography, reduction of stress levels as demonstrated through increases in left-sided activation in the anterior cortex, and reduction of pain processing.[22-30] Having established the positive health benefits of mindfulness, a more extensive look at the brain regions involved in responding functionally and structurally to mindfulness interventions is the major focus of this review. Understanding these mechanisms will allow clinicians to apply mindfulness interventions with greater specificity as it relates to therapeutic benefit.

Concentrative meditation is easier to operationally define than mindfulness meditation due to its relative simplicity. Ivanovski and Malhi, defining concentrative meditation as a process, state that the technique:

> involve[s] the focusing of attention on a mental 'object', for example, counting or monitoring breathing, reciting a mantra or visualizing processes in the body, to still the mind and enhance clarity and awareness. In these forms of meditation [concentrative], the individual *narrows* their attentional focus. Specific styles include Transcendental meditation (TM), Qiyong Yoga, Yoga Nidra, Sahaja Yoga and Samatha [Buddhist concentrative] meditations.[9] (77)

The authors characterize mindfulness, on the other hand, as involving "the expansion of attention in a nonjudgmental and nonreactive way to become more aware of one's sensory, mental and emotional experiences. This technique requires *expanding* awareness" (77). It is natural to assume, based on the definition of meditation as mindfulness-based or concentrative, that the discoveries of functional imaging would differ, as brain region activation is dependent on how the brain is being utilized.

Though the clinical effects of meditation and its psychosocial relevance have and continue to be investigated in detail, the examination of meditation and its neural correlates through functional imaging is still in the early investigative stage. While exciting studies confirm that meditation practice--both short and long-term practice--effectively alters the capability (functional change) and capacity (structural change) of the human brain as it relates to positive increases and alterations in attentional processing, the available literature is not yet deep enough to conclusively determine the role meditation might ultimately play in western healthcare. It is quite possible that because of the far-reaching positive effects of meditation practice, the behavioral intervention finds its niche in several healthcare fields and disciplines. Despite the absence of a substantive body of studies, research is being supported by major universities and institutions, and a number of studies have already been repeated. There is no doubt, based on the evidence, that meditation could potentially play a major role in western health, as it pertains to both prevention and management. For example, the work of Pagnoni *et al.* (2007) alludes to the neuroprotective effects of meditation, and its possibility of playing a role in curtailing memory loss in older populations. As mentioned, a number of studies have shown the ability of meditation practice to stimulate immune function and evade chronic pain, including low back pain. [4,31]

This review aims to examine the body of research presently available on the neural correlates of meditation through the use of functional imaging, including PET, SPECT, EEG, ECG, MRI, and fMRI. Based on the available research, two primary categories relating to the neural correlates of meditation are examined in this review: 1) brain region activation, which is further subdivided into mindfulness meditation and concentrative meditation, and 2) cortical thickening.

Methods

A literature search was performed on PubMed and MEDLINE using the keywords "meditation," "mindfulness," "brain," "neural correlates," and "neuroimaging." The criteria for inclusion was dependent on the utilization of functional imaging to investigate the neural correlates of meditation. The functional imaging modalities required for inclusion in this review were PET, SPECT, EEG, ECG, MRI and/or fMRI. *[TO INCLUDE: how many articles called, how many kept, what years catalogued]*

Discussion

I. Brain Region Activation

Meditation practices are especially suited to the presently available functional imaging techniques due to the ability of meditation practitioners to remain still while performing specific tasks. The primary signifiers of brain region activation are functional changes during meditation practices, and structural changes as a result of meditation practices. As mentioned, there are two categories of meditation: mindfulness and concentrative. Studies are reviewed here that use functional imaging to convey useful information regarding the nature of brain region activation during or as a result of meditation practices of the two categories of meditation.

A. Mindfulness Meditation

Creswell *et al.* examined mindfulness, defined as "a process whereby one is aware and receptive to present moment experiences," in a 2007 study, *Neural Correlates of Dispositional Mindfulness During Affect Labeling.*[32] Both trait mindfulness (mindfulness qualities inherent to the personality of a person prior to engagement in mindfulness practices) as well as mindfulness practice interventions have been shown to "reduce the negative affect, stress, mood disturbance, and disease-specific health symptoms across many patient population" (1). However, as indicated by the authors, what is still uncertain is exactly *how* mindfulness contributes to these effects. Participants in this study were initially asked to indicate trait levels of mindfulness, which was followed by the completion of an affect labeling task. The participants were then evaluated by fMRI.

The process of affect labeling is similar to strategies employed in Buddhism, the birthplace of mindfulness practice. It involves labeling cognitive emotional experiences as a means to distance or detach from them. For example, if one were to become angered, he or she would stop prior to acting on that emotion and label it (e.g., "anger has arisen"). Additionally, affect labeling can include briefly describing how one *wants* to feel: "I can complete this task without stress." Such affect labeling techniques garner a greater sense of control over one's emotions, which translates into a demonstrable, positive affect on one's actual ability to utilize positive emotions and curtail the harmful effects of negative emotions. Creswell *et al.* note that based on previous research, it is plausible to conclude that the "process of verbally labeling affective stimuli may disrupt or inhibit automatic affective responses, reducing their intensity and duration" (1). Verbal labeling of affective stimuli has been shown by the authors in previous studies to activate the right ventrolateral prefrontal cortex (VLPFC), as well as attenuate responses in the amygdala (1). Monk *et al.* suggest that an increased right ventrolateral prefrontal cortex response is associated with a decrease in experienced anxiety among adolescents with generalized anxiety disorder.[33] Additionally, an increase in VLPFC activity positively affects the amygdala, decreasing its activity and reducing experiences of fear and anxiety.[32] It is hypothesized that top-down prefrontal cortex (PFC) inhibition of limbic responses is responsible for this increase in VLPFC response and subsequent decrease in amygdala efferent responses. In this study, the authors tested the hypothesis that "dispositional mindfulness would be associated with greater activation in areas of the PFC (MPFC, right VLPFC), and would be associated with a concomitant deactivation of the amygdala during affect labeling" (1-2).

Participants completed the MAAS prior to participation in the study and were given labeling tasks while undergoing fMRI. Statistical analysis of the pre-participation responses and the fMRI results indicated that greater levels of trait mindfulness were positively and significantly associated with greater activity in the PFC during affect labeling. Mindfulness levels were also associated with greater activation in the right VLPFC, left VLPFC, ventromedial prefrontal cortex (VMPFC), MPFC, right dorsolateral prefrontal cortex (DLPFC), and left insula. Greater mindfulness was associated with a bilateral deactivation in the amygdala during affect labeling. Further detailed analysis of the fMRI results demonstrated that greater mindfulness was also associated with more *efficient* PFC inhibition of the amygdala, while low mindfulness alluded to no association.

Holzel *et al.* used fMRI to investigate mindfulness meditators with a mean practice of 7.9 years for two hours per day as compared to non-meditator controls.[34] They found that meditators demonstrated a greater activation of the rostral anterior cingulate cortex and dorsal medial prefrontal cortex bilaterally. The authors hypothesize that the greater activation in the rostral anterior cingulate cortex could signify more efficient processing of distracting events, and the increased activation in the medial prefrontal cortex may indicate a stronger engagement in emotional processing.

Farb *et al.* sought to evaluate the neurological alterations and/or differences of two forms of temporal self-reference.[36] The first, extended self-reference linking experiences across time is termed "narrative focus" (NF). The second, momentary self-reference centered on the present is termed "experiential focus" (EF). In meditation practice, and especially mindfulness practices, EF is sought ("cultivated") while NF is given progressively less attention through training, or altogether avoided. NF, as the theory of narrative generation most common to the daily concept of "self," is also demonstrated to be the mind's most frequent mode of activity, as supported by neurological evidence in the work of Mason *et al.* (2007), who showed that cortical midline activity characterizes NF.[37] Gusnard *et al.* (2001) and Raichle *et al.* (2001) call this activity the "default mode" of resting attention.[38,39] In contrast to this 'default mode,' EF involves attentional control and moment-to-moment monitoring not characteristic of the majority of daily attention.[36] This form of conscious awareness is exemplified in mindfulness, and involves concerted training like that found in Buddhist meditation practice and MBSR. The result of continued EF generation through the practice of mindfulness is a decrease in NF through two proposed mechanisms: the development of inhibitory mechanisms to prevent NF generation, and/or the fundamental shift away from NF as the 'default mode' of resting attention (5).

Farb *et al.* enlisted participants from St. Joseph's Hospital in Toronto to participate in an eight-week MBSR program. The participants were taught the differences between NF and EF, and after sufficient assimilation of the differences were asked to describe the differences in their own words. They were subsequently taught how to access NF and EF through self-focus tasks, and how to engage NF or EF during the research evaluation. fMRI was utilized during the performance of self-focus tasks and two comparisons were made in the experiment relating to group (novice/untrained vs. mindfulness-trained) and self-focus (narrative vs. experiential). The results indicated that NF was more easily accessed than EF, and mindfulness-trained participants had an easier time accessing *both* NF and EF when compared to novices (untrained participants). fMRI results indicated that NF led to an increase in midline cortical activation, as previously thought and demonstrated. Brain regions activated during EF include the rostral and dorsal mPFC, posterior cingulate, left hemisphere language areas, including inferolateral PFC, middle temporal gyrus, left hippocampus, right inferior frontal gyrus, right precentral gyrus, cuneus, left head of caudate and cerebellum. In the EF novice participants, reduced activity was noted in the midline cortical region, and specifically gyrus rectus of the subgenual cingulate, posterior cingulate and rostral mPFC. A relative increase in left lateralized regions including dorsolateral PFC, ventrolateral PFC and posterior parietal cortices. Comparing EF in mindfulness-trained subjects, increased left-sided dorsolateral and posterior parietal recruitment, as the authors of this study point out, could indicate "greater task-related executive control and attentional allocation or at the very least, an attempt to resist narrative mind wandering," claims supported in the work of Gusnard *et al.,* 2001 and Mason *et al.,* 2007.[38,37] EF experience in the mindfulness-trained group demonstrated deactivations in the anterior cortical midline, and specifically the rostral subregions of the dorsal mPFC, ventral mPFC and left dorsal amygdala. Thus, it is potentially the inhibition of mPFC activity that allows for the successful employment of EF. There was noted increase in recruitment of a right lateralized cortical network, which included the dorsal and inferolateral PFC, insular cortex, a region along the supramarginal gyrus consistent with the secondary somatosensory cortex extending posteriorly and dorsally into the angular gyrus of the inferior parietal lobule. The authors remark that, "This pattern is consistent with the MT group demonstrating a marked shift from midline mPFC-centred recruitment towards right lateralised prefrontal cortical and paralimbic structures, in particular demonstrating recruitment of hypothesised posterior viscerosomotic representations" (6). EF when compared to NF indicated that reduced activity was found in the ventral and dorsal mPFC in the mindfulness-trained group only. EF led to increased activity in the right lateral PFC, right insula and SII/inferior parietal lobule in the mindfulness-trained group but not the novice group. The researchers discovered that the novice group most likely had a more difficult time employing EF vs NF because of their inability to decouple the strong viscerosomatic impulses generated during self-reference *in general.* The viscerosomatic pathway was demonstrated, after functional connectivity assessment between viscerosomatic corticies and mPFC across time, to be most strongly connected with midline cortical to vmPFC-insula pathway activation. Thus, mindfulness-trained participants have likely developed a neurological strategy for decoupling the vmPFC-insula pathway, allowing for a moment-to-moment awareness to manifest. Looking at the mindfulness-trained participants, Farb *et al.* found that there was no correlation between the right insula and vmPFC, and that there was a correlation between the right insula and dorsolateral prefrontal cortex. In conclusion, this work supports the notion that mindfulness, and specifically the experiential-focus of "moment-to-moment" awareness that it cultivates promotes the integration of viscerosomatic activity through the lateral PFC rather than the more common mPFC, the end location of narrative focus self-reference activity.

Among the most important populations of extensively trained mindfulness meditation practitioners are Zen Buddhists. Zen meditation is the most widely recognized form of mindfulness meditation, and in particular through its mindfulness sitting practice most commonly known through its Japanese term, *zazen*. During *zazen*, or seated mindfulness practice, the practitioner engages a mental activity that is receptive of all sensory experience in a nondiscriminatory manner, such that no preferences are granted to sight, sound, taste, touch, smell or thought. David E. Shaner, PhD, an expert in Japanese Buddhist philosophy at Furman University states that a motivation for such practice and as a consequence of such practice, a sense of *selflessness* is engendered, through the progressive "dropping off" of attachments of both sensory experience and thought objects.[40] Pagnoni *et al*, state:

> while particular meditative practices attempt to promote absorption and sensory withdrawal from the environment, Zen meditation, quite to the contrary, prescribes a vigilant attitude that is pragmatically implemented by the adoption of a seated posture with a certain degree of active tension by keeping the eyes open; mental withdrawal from the environment is considered as promoting a state of dreaminess and lack of clarity counterproductive to the meditative pursuit and is therefore vigorously discouraged.[41] (1)

The previous work of Raichle *et al.* has alluded to a "default mode" of brain activity--the activity employed most of the time--lends itself to experiential discrimination, which in turn generates a rigid "sense of self."[39] Pagnoni *et al.* seek to test the hypothesis that when compared to control subjects, regular meditators have the ability to "voluntarily contain the automatic cascade of conceptual associations triggered by semantic stimuli" (2).[41] Using a simple lexical decision task which has test subjects (meditators) and controls (non-meditators) determine the meaning of words and nonwords, the researchers evaluated the two groups using fMRI. Participants were asked to focus on their breathing between words-nonwords propositions. It was discovered that while the reaction times and number of errors were similar between the two groups, the amount and degree of brain activity *in between* the words-nonwords testing (i.e. when returning awareness to breathing) was significantly less in the group of Zen meditators, indicating the the amount and degree of rumination was less among Zen meditators. While the brain regions associated with the processing of semantic information was active in both meditation and control groups, this is expected due to the nature of the lexical decision task chosen for this study. However, fMRI evaluation demonstrated that the meditation group more quickly deactivated areas involved in semantic processing once it was no longer needed to complete the task; such areas involved in semantic processing include angular gyrus, medial parietal cortex and areas of the prefrontal cortex. The control group elicited a sustained semantic processing response even when the lexical decision task was completed, indicating that the brain of non-mediators is more prone to rumination.

One study examined brain region activation differences in control (non-mediators) vs meditation and short-term meditators (<10 years) vs long-term meditators (>10 years), and confirmed further findings relevant to this discussion.[42] Using region-specific and time-sensitive approaches with fMRI, the researchers confirmed increases in activity in the groups of meditators when compared to controls in the DLPFC and anterior cingulate cortex (ACC). The DLPFC and ACC are well documented in the involvement of attentional control, including selective attention, attention shifting, attention monitoring and response selection. As meditation in general (including both mindfulness and concentrative categories) involves the employment of either more global awareness or focused awareness, it fits that the DLPFC and ACC are more active in the brains of meditators regardless of specific category. The take-home point here is that all meditation (this study included practitioners of Zen Buddhism, Tibetan Buddhism and Hindu Yogic traditions), as a concerted practice, involves a greater employment of attentional reserves than average, everyday awareness of the "default mode" of brain activity. When comparing short-term mediators to long-term meditators, it was observed that short-term meditators had a more difficult time maintaing increased activation of the DLPFC and ACC, and in fact a decrease in activation was noted over time. On the contrary, long-term meditators not only maintained increased activation of the DLPFC and ACC but continued to increase its activation over time.

The regional cerebral blood flow (rCBF) of long-term Tibetan Buddhist meditators was evaluated using positron emission tomography (PET).[43] After 60 minutes of meditation, the practitioners' cCBF changed significantly as compared to baseline readings in the cingulate gyrus, inferior and orbital frontal cortex, DLPFC and thalamus. Also noted was the negative correlation between change in the left DLPFC and the left superior parietal lobe. The authors note that it is expected to see increased metabolic activity in the frontal and thalamic regions of the cortex due to the enhanced awareness experienced by meditation. One hypothesis put forward by the authors to explain the DLPFC-superior parietal negative correlation is an altered sense of spatial experience often described in meditators.

Using EEG, Davidson *et al.* demonstrated significant increases in left-sided anterior activation, a brain region associated with positive emotional affect, in meditators trained in MBSR.[44] A significant decrease in negative emotional affect was noted in the same population correlated with mindfulness training.

B. Concentrative Meditation

Concentrative meditation is the second category of meditation, which is defined by "narrow focus" sensory experience, or "single-sensory" meditation, where one sensory modality is preferenced over others. While most studies confirm specific brain region activations as a result of the specific sensory function employed during concentrative meditations, some, like *Herzog et al.* found using PET that during Yoga concentrative meditation, the behavior of brain metabolism shifted to a more integrated and holistic function when compared to non-meditative or average, everyday consciousness.[54] However, a shift towards a more holistic brain function is only comparable to the manner in which the brain is used *most of the time* and does not exclude additional specialization in function, which are examined here.

Lehman *et al.* confirmed using EEG that during specific subtypes of concentrative meditations, discrete regions are active.[45] During visualization, the right posterior cortex is active, whereas the left central cortex is active during verbalization, such as mantra or chanting. This finding is significant, as it illustrates that specific types of meditation practice lead to specific types of brain region activation. This lends credence to the hypothesis that the type of brain training engaged such as mindfulness vs. concentration meditation and their subtypes cultivates the kind of brain function required for such training. The implications of this are positive for performance enhancement, where certain types of awareness, focus or brain function is sought.

Kakigia *et al.* examined a Yoga master who claimed to feel no pain during meditation.[46] Yogic traditions often employ a concentrative meditation technique which focuses on the dissolution of the self through progressive introspection. Using magnetoencephalography (MEG) and fMRI, researchers applied a painful laser stimulus to the Yoga master and recorded his brain activity. The MEG imaging demonstrated that alpha wave production increased generally in the occipital, parietal and temporal regions when compared to a non-meditative state. As might be expected, primary and secondary pain processing centers in the SI and SII somatosensory cortices were weak to absent on MEG. fMRI showed significant decreases in activity of the thalamus, SII-insula and cingulate cortex during meditation, a finding that is reversed during non-meditation.

Yoga Nidra is a type of concentrative meditation technique that focuses on "desireless being," a state by which the practitioner is positively uninterested in having, maintaining or creating motivation for action. This kind of meditational focus is characterized by decreased blood flow in the prefrontal, cerebella and subcortical regions, all areas responsible for executive function. Using PET and EEG, researchers examined the release of dopamine during Yoga Nidra and discovered that endogenous dopamine increased by 7.9% in the ventral striatum during meditation, and was associated with EEG theta activity in addition to a reported decrease in desire for action and a heightened sensory imagery. A proposed hypothesis is that meditation such as Yoga Nidra suppresses the cortico-striatal glutamatergic communication pathways. The authors note the significance of this study as *in vivo* evidence of neuronal regulation of conscious states.

A common concentrative technique employed in Buddhist traditions of all varieties is "compassion meditation," whereby practitioners intentionally cultivate a sense of compassion for self and other; this is commonly referred to as "loving-kindness" meditation. Lutz *et al.* state that during such empathy-dominant affective processing, brain regions such as the insula and ACC are known to be implicated.[47] They call this particular meditation the loving-kindness-compassion meditation state. To test their hypothesis that regions previously demonstrated to be involved in empathy procession--such as the insula and ACC--are in fact involved during the generation of empathy, they present test and control subjects with emotional sounds and neutral sounds while undergoing fMRI evaluation. Long-term meditators (>10,000 hours of training) from Buddhist communities were evaluated and compared to novices who had no previous meditation experience. The particular loving-kindness-compassion prompt used during the study was an "unconditional feeling of loving-kindness and compassion [which] pervades the whole mind as a way of being, with no other consideration, or discursive thoughts." The authors note that within the Buddhist traditions employing empathy-dominant affective processing, the goal is to orient the mind towards a more immediate and receptive empathetic response so that when the occasion for its employment arises, it is more readily employed. Results of the study confirmed that long-term meditators experienced (through verbal confirmation) and neurologically produced (through fMRI confirmation) brain region activation consistent with expected empathy processing, and that the degree of brain region activation correlated with verbal reporting of the intensity and depth of loving-kindness-compassion meditation. This was seen only during emotional sound exposure. Consequently, the practice and internal generation or "voluntary regulation" of a loving-kindness-compassion state modulated the actual experience of emotional sounds (positive or negative sounds) when a practitioner is exposed to them, a finding consistent with the perception-action model of empathy. For the purposes of this review, it is important to note how this study supports the idea that the effects of meditation as they relate to brain region activation is directly correlated to the kind of meditation practice one engages. For example, in loving-kindness-compassion meditation practice, where the orientation and goal of the practitioner is to experience a deeper level of empathy, this is indeed the result confirmed by functional imaging. In contrast and as demonstrated in the studies outlined above, mindfulness meditation, which attempts no specific enhancement in awareness but a general expansion of sensory experiences of all kinds.

A study of particular interest was performed by Shimomura *et al.* using fMRI on Buddhists performing two verbalization practices, chanting and recitation.[49] In chanting, a short, repetitive statement or invocation is made during traditional Buddhist practice that induces a trance-like concentrative experience. Though similar, a recitation in Buddhist practice usually involves the verbalization of a sutra, which is a longer text. In this study, a common chant called the Nembutsu ("*namu amida butsu*") is repeated throughout the duration of the meditation practice. Sutras are much longer in content and complexity and require a different level of attentiveness, a fact reflected in the different regional activations in the brain according to the kind of verbalization practice. Shimomura *et al.* found that repeating the chant (Nembutsu) activated primarily the prefrontal cortex, specifically the medial frontal gyrus, an area known to be related to concentration and visuospatial attention. The sutra recitation activated the left dorsolateral prefrontal cortex and right parietal cortex, and specifically the left lateral middle frontal gyrus, the right angular gyrus, and the right supramarginal gyrus, all areas known to be related to visuospatial attention. This study is perhaps the only study to confirm differences in brain region activation associated with two different types of verbalization techniques.

Brefcynski-Lewis *et al.* evaluated the differences between brain region activation using fMRI in novices vs expert meditators, defined here as having an average of 19,000 hours of practice or greater.[50] Meditators were matched with controls for gender, age, and culture. A concentrative meditation task was given to Both novices and expert meditators involving shifting between attentional focus on a small dot on a screen ("one-pointed concentration") with a neutral resting state to provide a block paradigm. A distracting external stimuli (positive, negative or neutral sounds) was introduced using event-related cues during portions of the meditation and rest blocks. The results of this study demonstrated that both experts and novices elicited similar activation of attention-related brain regions such as the frontal parietal regions, lateral occipital, insula, multiple thalamic nuclei, basal ganglia and cerebellar regions, and as suggested by the authors this is likely in response to the dot-following portion of the concentrative exercise. Novices but not experts additionally demonstrated higher activation of the medial frontal gyrus/anterior cingulate cortex and right mid-insula to posterior-insula regions. Authors such as Lawrence *et al.* and Schulz *et al.* have previously shown such areas to be negatively correlated with attentional performance.[59,60] Brefczynski-Lewis *et al.* predicted and confirmed that novices demonstrated less activation in attentional processing regions than expert meditators. However, the degree of region activation among meditators demonstrated a U-shaped curve, where the most experienced meditators elicited *less* activation than intermediately-trained meditators; the authors hypothesize that this variation is accounted for by the greater relative ease of attentional processing by the most experienced meditators due to brain plasticity.

Like mindfulness meditation, concentrative meditation has also demonstrated the ability to diminish pain processing. One of the most extensively studied concentrative meditation techniques is Transcendental Meditation (TM), which is a form of mantra or chanting practice. In a study conducted by Orme-Johnson *et al*, TM was used to evaluate the brain region activation in long-term practitioners when compared to novices (those who want to learn TM but have no experience) during the application of a noxious stimulus. [51] The authors point out the discovery of the "pain matrix" in neuroimaging studies performed since the 1990s. While much has been learned about bottom-up and top-down pain processing in the central nervous system, much remains to be learned as a comprehensive theory is not yet available. To summarize a number of points highlighted by this review, Orme-Johnson *et al.* state the following:

> Different meditation techniques have different effects on the brain that are specific to the cognitive requirements of the techniques and may affect pain differently. We suggest four mechanisms by which meditation could reduce pain: (1) distract attention away from it; (2) resolve the underlying physiological condition responsible for chronic pain; (3) reduce anticipatory anxiety and general stress reactivity and other factors that amplify the pain response; and (4) reduce pain-related distress, perhaps through increasing endogenous endorphins.

TM, according to the authors, utilizes mechanisms 2-4 in order to dampen the pain experience. Using fMRI, this study evaluated the brain activation in response to pain in long-term TM practitioners and novices. The Visual Analog Scale (VAS) ratings of both groups remained comparable throughout the study in pretest, posttest and during testing, and both groups revealed a 25% decrease in VAS scores five months after initial testing. Nonetheless, significant differences were discovered on functional imaging in the brains of the two groups. The long-term TM practitioners initially demonstrated a 40-50% reduction in brain activation in regions known to be involved in pain processing; this same reduction was also demonstrated in the novice group five months after initial testing as a result of TM training during this interval. Pain processing regions included the ACC, PFC, and thalamus.

Yoga Nidra is a meditation technique that relies on the termination and elimination of motivated action, involving extensive practitioner concentration. PET scans performed by Lou *et al.* revealed that Yoga Nidra practitioners, when compared to the resting consciousness of nonpractitioner controls exhibited increased perfusion in sensory imagery systems, specifically the hippocampus and related sensory and higher order association regions. [52] Decreased metabolic activity was noticed in the executive system, specifically the dorsolateral prefrontal cortex, anterior cingulate gyrus, striatum, thalamus, pons, and cerebellum, a finding also confirmed by a previous study using PET and EEG by Lou *et al* (1999). [53] This is consistent with the verbal self-report of Yoga Nidra practitioners where executive function is consciously minimized.

Lazar SW *et al.* sought to evaluate the neurobiological underpinnings of meditation using a simple form of concentrative meditation. [55] Focusing on the concomitant positive physiological effects of meditation which comprise the "relaxation response" first described by cardiologist Herbert Benson, the authors explain the hypometabolic-inducing effects of meditation as well as the alterations in EEG patterns. Slowed EEG patterns suggest a physiological relaxation response, and demonstrable decreases in blood pressure and increases in blood oxygen saturation levels during meditation are two physiological effects that could potentially benefit cardiorespiratory patients. In conjunction with cardiorespiratory measurements during this study, Lazar et. al. utilized fMRI. Using Kundalini meditation, a form of concentrative meditation that focuses on the breath while silently repeated the mantra 'sat nam' during inhalations and 'wahe guru' during exhalations, the researchers evaluated five right-handed subjects aged 22-45 using fMRI during the Kundalini (concentrative) meditation and during a control exercise. As hypothesized, significant increases in neural structures associated with attention and arousal were noted on fMRI. Specifically, increases were observed in the putamen, midbrain, pregenual anterior cingulate cortex and hippocampal/parahippocampal formation. When comparing late vs. early meditation in the meditation phase, increases were found in the prefrontal, parietal and temporal cortices, and the precentral and postcentral gyri and hippocampal/parahippocampal formation.

Experience-Dependent Differences

II. Cortical Thickening

Recently, researchers in meditation studies have discovered *structural* changes to the cortex of long-term meditators. Holzel *et al.* applied MRI to mindfulness meditation practitioners with an average of 8.6 years of practice for two hours per day.[56] Researchers compared the gray matter concentration of meditators with non-meditator controls matched for gender, age, education and handedness. A significant increase in gray matter concentration was noticed in the brains of mindfulness meditation practitioners, specifically in the right anterior insula, an area known to be involved in interoceptive awareness and an area implicated in the employment of mindfulness. Increases in gray matter concentration was additionally noticed in the left inferior temporal gyrus and right hippocampus. As Lazar *et al.* also revealed, cortical thickness correlated with meditation experience, and particularly in the left inferior temporal gyrus.[55]

Citing previous EEG studies of meditation that confirm lasting changes in brain activity, Lazar *et al.* were the first to investigate the possibility of regular meditation practice on the structure of the brain.[58] Using MRI, meditators of the Insight meditation tradition (a common form of internally-focused concentrative meditation) were evaluated for structural alterations. It was discovered that areas involved in attentional processing were thicker in the meditators when compared with matched nonmeditator controls. In particular, the prefrontal cortex and right anterior insula were significantly thicker in the meditators. The amount of meditation training correlated with increasing thickness of cortical gray mater. These striking and impressive results, the authors suggest, indicate a large degree of plasticity in the adult brain that is stimulated by meditation practice. The authors suggest that such increases in cortical thickness could potentially counter age-related thinning.

In 2007, Pagnoni *et al.* examined this question posed by Lazar *et al.* regarding the potentially offsetting effects of meditation practice on age-related cortical thinning.[58] Researchers looked at the variations in cortical thickness of Zen meditators and age-matched nonmeditator controls. As was hypothesized, the nonmeditators exhibited a loss of gray matter volume *and* attentional performance, as measured with voxel-based morphometry of MRI images while subjects performed a basic attentional task. Zen meditators, on the contrary, did not demonstrate a correlation between age or attentional performance and age, confirming that regular meditation practice, in this case mindfulness meditation of the Zen Buddhist tradition, was sufficient to stimulate and maintain the functional capacity of the cortex through an increase in structural volume. Of particular note was the more prominent thickness in meditators in the putamen, which is regarded for its role in attentional processing. Pagnoni *et al.* have opened the door to an exciting and remarkable discovery that regular meditation practice can have neuroprotective effects by preserving or reducing age-related changes in cortical thickness and, consequently, attentional processing.

Conclusion

Exciting and potentially far-reaching discoveries are emerging in meditation research using functional imaging. For both therapeutic and performance-enhancement benefits, meditation practice, in both of its two forms, mindfulness and concentrative, are consistently demonstrating significant functional changes in the human brain. Additionally, more recent research has shown that structural changes occur over time in the brains of meditators. The stage is set for deeper investigation into the specific implications of the functional and structural alterations in the brains of persons who engage in meditation practices.

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