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Neuroplasticity induced by meditation practices: A systematic review

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Abstract

Meditation has in recent decades received attention mainly for its health benefits in western society, not least in the field of neuroscience. Researchers are frequently exploring the link between plasticity in the brain, and the practice of meditation. This systematic review aims to investigate the underlying functional and structural differences in brain mechanisms between long-term meditators and non-meditators, involving different meditation forms. A total of seven peer-reviewed articles were included after being screened for, and meeting inclusion criteria. Final outcomes demonstrated differences between meditators and non-meditators in both functional and structural measures. Some brain regions where changes were identified in meditators included higher-order cognitive areas (i.e., frontal and temporal brain regions). These brain regions are known to be involved in emotional, attentional and memory processing. Reduced connectivity within the default mode network (DMN) is known to be associated with meditation, which was supported in two of the studies. Furthermore, larger gray matter density was found in autonomous control centers (i.e., the brainstem), and larger callosal thickness in meditators. Based on the findings, the practice of long-term meditation appears to be linked with functional and structural changes in various regions of the brain. The findings give insight into the underlying neural correlates and brain plasticity in meditators compared to non-meditators. Nevertheless, future research is necessary for understanding the long-term effects of various meditation forms.

Keywords: meditation, neuroplasticity, fMRI, MRI, wellbeing

Neuroplasticity induced by meditation practices: A systematic review

In recent years, our understanding of how the brain works has gone through great progress. Neuroscience has brought insight into the scientific view of the human mind and its underlying nature. As a result of neuroscience and its tools emerging and developing, one of the topics that has caught attention in recent years is the concept of neuroplasticity: the brain's ability to alter and adapt to new experiences and situations (Baer, 2010). Specifically, *neuro* refers to the neurons and nerve cells, and *plasticity* to the adaptability in the brain (Das, 2014). For a long time, the human adult brain was considered in Western culture to be unchangeable in its structure and function, but in the last decades, scientists have conducted a large number of studies that have been able to prove the opposite (Costandi, 2016). This shift in knowledge has contributed to the phenomena gaining attention within neuroscience as well as in the general public. When searching for the concept on the internet it is tempting to want to learn more when the first search results that appear involve "rewire your brain to thinking positive" or "train your brain to become more motivated". However, it is not as simple as it may sound. First, the term neuroplasticity and its definition are somewhat vague and specified differently depending on what kind of brain area is being researched or for what purpose (Maino, 2009). Costandi (2016) describes how the alterations in the brain when talking about neuroplasticity can generally be put in two main categories: Structural changes and functional changes. Structural changes involve alterations in the volume in distinct brain areas and the formation of new neural pathways, whereas functional changes include alterations in a certain physiological feature of the nerve cell function. Simply put, neurons that are frequently used build stronger connections, whilst those who are rarely or never activated sooner or later die (Hutchins & Barger, 1998).

Neuroplasticity has been explored from various perspectives and for different purposes, such as learning new things, engaging in physical activities, recovering from a stroke, or how expressing a positive emotion such as gratitude can lead to changes in brain activity (Kini et al., 2016). One specific area that has been questioned and studied concerning changes in the human brain is the effect of meditation, and whether it can induce plasticity (Van Dam et al., 2018). Meditation is a practice that trains the mind to be aware and attentive, with the goal often being to reach "enlightenment", which Davis and Vago (2013) suggest in modern translation means knowledge or wisdom. As a result of Eastern spiritual traditions gaining more enthusiasm in Western culture, the practice of different meditation techniques and their associations to alterations in the brain has been growing in interest amongst cognitive neuroscientists. Researchers are interested in exploring if meditation can affect neuroplasticity and the possible underlying mechanisms involved.

Types of Meditations

There are numerous different ways to practice meditation that vary in their origin, technique, and subjective experience. This has contributed to a subtle nature of the concept that can be somewhat difficult to define, and a lack of a unified term exists within the field (Simkin & Black, 2014). In general terms, meditation can be defined as a set of techniques aimed to foster relaxation and a heightened sense of well-being (Davidson & Lutz, 2008). Since Eastern meditation practices were introduced into Western society, some defined meditation in a neurological way as "a complex neural practice that induces changes in neurophysiology and neurochemistry of the brain, resulting in altered neurocognition and behavior in the practitioner" (Jaseja, 2008, p. 1). Two common types of meditation that neuroscientists have been exploring in recent years include focused attention (FA) and open monitoring (OM). FA meditation practices involve focusing the attention on a single object situated in the present moment (e.g., the breath or sensation) to cultivate attentional control skills. In OM meditation, the practitioner persists his attentiveness and openness to stimuli that arise from moment to moment, essentially intending to recognize the nature of emotional and cognitive patterns (Davidson & Lutz, 2008). Many forms of meditation involve both FA and OM, including mindfulness meditation, one of the most popularized practices introduced to Western culture and clinical psychology. Jon Kabat Zinn, a prominent researcher in the field states the concept as "paying attention in a particular way: on purpose, in the present moment and nonjudgmentally" (Kabat-Zinn, 2009.) The practice involves focusing on stimuli that happen in the now such as the breath, thoughts, feelings, sensations, or sounds. The experiences are to be observed without judgment regardless of whether they feel pleasurable or not (Baer, 2003). Mindfulness meditation is to this date frequently explored and used in the treatment of health concerns such as relieving stress symptoms, anxiety, depression, and physical pain (Hoffman & Gomez, 2017). Such practices include Mindfulness-Based Stress Reduction (MBSR) and Mindfulness-based cognitive therapy which within the cognitive and motor skill literature are treated as a skill that can be learned (Baer, 2010). Additional examples of FA meditation include practices that focus on the inhale and exhale of the breath such as Zen meditation, mantra meditations, and Vipassana meditation (Godfrin & Heeringen, 2010). Another form of meditation rooted in Buddhism tradition that has increased interest in Western psychology and science is loving-kindness meditation (LKM). The practice aims to cultivate genuine and kind intentions towards oneself, loved ones, or neutral individuals or groups of individuals. Statements repeated during LKM include "may you be free from suffering" or "may you be happy" (Zeng et al., 2015), which promotes openness, present-centered awareness, and selfless love in the practitioners. LKM is suggested in previous studies to foster positive emotions, decrease negative emotions, and reduce mind wandering, and has been shown to ease depressive symptoms, stress, and social anxiety in particular (Garrison et al., 2014). The promising psychological health benefits have been engaging researchers to further investigate the neural substrates of practicing LKM. Research has demonstrated meditation to obtain many positive health-related effects and is shown to boost performance on behavioral assessments of attention (Devaney et al., 2021).

Neural correlates of meditation

The brain networks involved when practicing meditation are nevertheless proceeding to be uncovered, and the underlying mechanisms are still being explored. Investigating the pathways in the brain associated with short (typically eight weeks or less duration of practice) and long-term meditation practice (more than eight weeks) may provide a further understanding of both functional and structural alterations in various brain networks (Kral et al., 2018). Studies that have been done on short-term meditation practitioners commonly integrate mindfulness-based clinical interventions, where the participants involved generally have little to no prior experience with meditation. It is of significance to study both novice and experienced meditation practitioners to understand its effect on health outcomes. However, to truly understand the underlying mechanisms involved with the 'enlightenment', that meditators can experience and whether it can induce plasticity in the brain, it is important to investigate the experienced individuals to uncover its most fundamental traits. This review will be based on the significance of identifying these traits including studies that focus on experienced meditation practitioners. Understanding long-term effects and the potential functional and structural brain differences is useful for the research question of if, and how it generates neuroplasticity. This information additionally provides valuable knowledge for the treatment of various mental disorders, and how to enhance well-being. From a neuroscientific point of view, meditation is a heterogeneous practice that requires an intense concentration ability as well as being attentive to stimuli such as the breath, thoughts or sensations. This has contributed to diverse findings depending on the type of meditation being studied. Nevertheless, various consistent results have been identified (Baer, 2003).

Researchers have been exploring changes that happen in the brain in experienced meditation practitioners as well as novices, largely with the help of brain imaging tools such as Magnetic Resonance Imaging (MRI), functional Magnetic Resonance Imaging (fMRI), and Electroencephalography (EEG; Berkovich-Ohana et al., 2014). Neuroimaging studies have reported changes in functional connectivity where the default mode network (DMN) is one of the central brain areas associated with a decrease in activation when engaging in meditation, particularly in mindfulness-based practices (Marchand, 2014). The DMN includes areas such as the medial prefrontal cortex, posterior cingulate cortex, and left temporoparietal junction which are accountable for attention and emotion regulation, mind-wandering, and self-referential thoughts (Scheibner et al,. 2017). More specifically, the brain regions involved in the DMN have been demonstrated to show reduced activity when engagement in a task is strong and requires our attention. In contrast, the same regions are showing higher levels of activity when we are awake, but not engaged in any task (Buckner et a., 2008). The practice of meditation has received awareness in neuroscience for having an impact on the DMN, which has led to more research in overall well-being and the treatment of mental illness (Garrison et al., 2015). Strong associations in the brain linked to mindfulness meditation have moreover been linked through network analyses of fMRI data, where activity in the frontal regions of the brain, anterior cingulate cortex (ACC), and insula which are areas involved in cognitive functions, were uncovered in novices and skilled meditators. Additionally, reduced brain cell volume in the amygdala, (primary role in emotional responses such as fear, and memory process) and cortical thickness increase in the hippocampus (a crucial area in the brain for regulating learning and memory) have been observed in meditators as opposed to non-meditators (Hölzel et al., 2011). These findings correlate with previous statements that indicate how mindfulness meditation is a learning skill, and that functional changes in the brain are associated with the amount of time meditation is being practiced (Falcone & Jerram, 2018). In long-term LKM practitioners, fMRI studies have shown a higher level of neural activity in the amygdala, ACC, and temporal-parietal junction. These regions are significant for identifying the value of emotional stimuli, affective states and regulation of emotional responses (Lutz et al., 2008). Additionally, greater functional connectivity between the posterior cingulate cortex/precuneus (PCC/PCu) and the left interior frontal gurys have been observed in skilled LKM practitioners. In comparison to novices, greater activity between PCC/PCu and other cortical midline regions of the default mode network was shown, suggesting that LKM is associated with present-centered and selfless areas (Garrison et al., 2014). Furthermore, structural changes have been shown in form of increased cortical thickness within certain brain areas. Kang et al. (2012) conducted an MRI study on 46 experienced meditators and an equal amount of meditation-naïve control groups where the meditators showed a greater cortical thickness in the medial prefrontal cortex, superior frontal cortex, temporal pole and the middle and inferior temporal cortices in meditators in comparison to the controls.

The findings indicate structural differences in white and gray matter in long-term meditators (Kang et al., 2012).

Interest in the field is frequently growing, though, there is a shortage of a consistent explanation of whether brain activation across different meditation forms and stages exists, especially engaging experienced practitioners (Wang et al., 2011). Understanding the underlying mechanisms is significant as it may provide further knowledge into various brain networks, how they are associated with specific meditation practices and whether they can induce neuroplasticity. Moreover, insight into the impacts of meditation and its different structural and functional mechanisms can help identify its usefulness in psychological treatments and overall well-being. Understanding the neural correlates related to different states of consciousness such as meditation can further lead to insights into the neural pathways of human consciousness (Winter et al., 2020). This systematic review aims to investigate the underlying functional and structural differences in brain mechanisms between long-term meditators and non-meditators, involving different meditation forms. By analyzing neuroimaging studies done on experienced meditation practitioners compared with non-meditators, insight may be brought into whether differences can be observed in regard to meditation experience. Additional reviews are important for further understanding the phenomenon of meditation and how different practices can be explored through their neural correlations. This information in turn provides knowledge about how different meditation forms can be practiced with the aim of improving well-being. It also allows fo a neuroscientific perspective of consciousness.

Methods

Search strategy

A literature search was conducted on the 24th of May 2022 in the electronic database Scopus to find relevant studies. The following search string was used: "meditation" AND ("neuroplasticity" OR "plasticity") AND (fMRI OR "imaging" OR EEG). No time limit was set.

The mentioned keyword combination found a total of 88 articles (see Figure 1) based on titles, abstracts, and keywords. All articles were exported into the Rayyan application, a helpful web-tool for systematic reviews (Ouzzani et al., 2016) to detect duplicates from where 4 were identified and removed. Of the 84 original articles, 31 were not measuring changes in the brain related to meditation. Out of the remaining 53 articles, 45 were irrelevant and removed based on the following exclusion criteria: Did not analyze changes in the brain related to meditation (n = 12), did not involve experienced meditators (n = 17), used other imaging methods (n = 16). Seven (n= 7) articles in total were included in the review matching the inclusion criteria.

Inclusion and Exclusion criteria

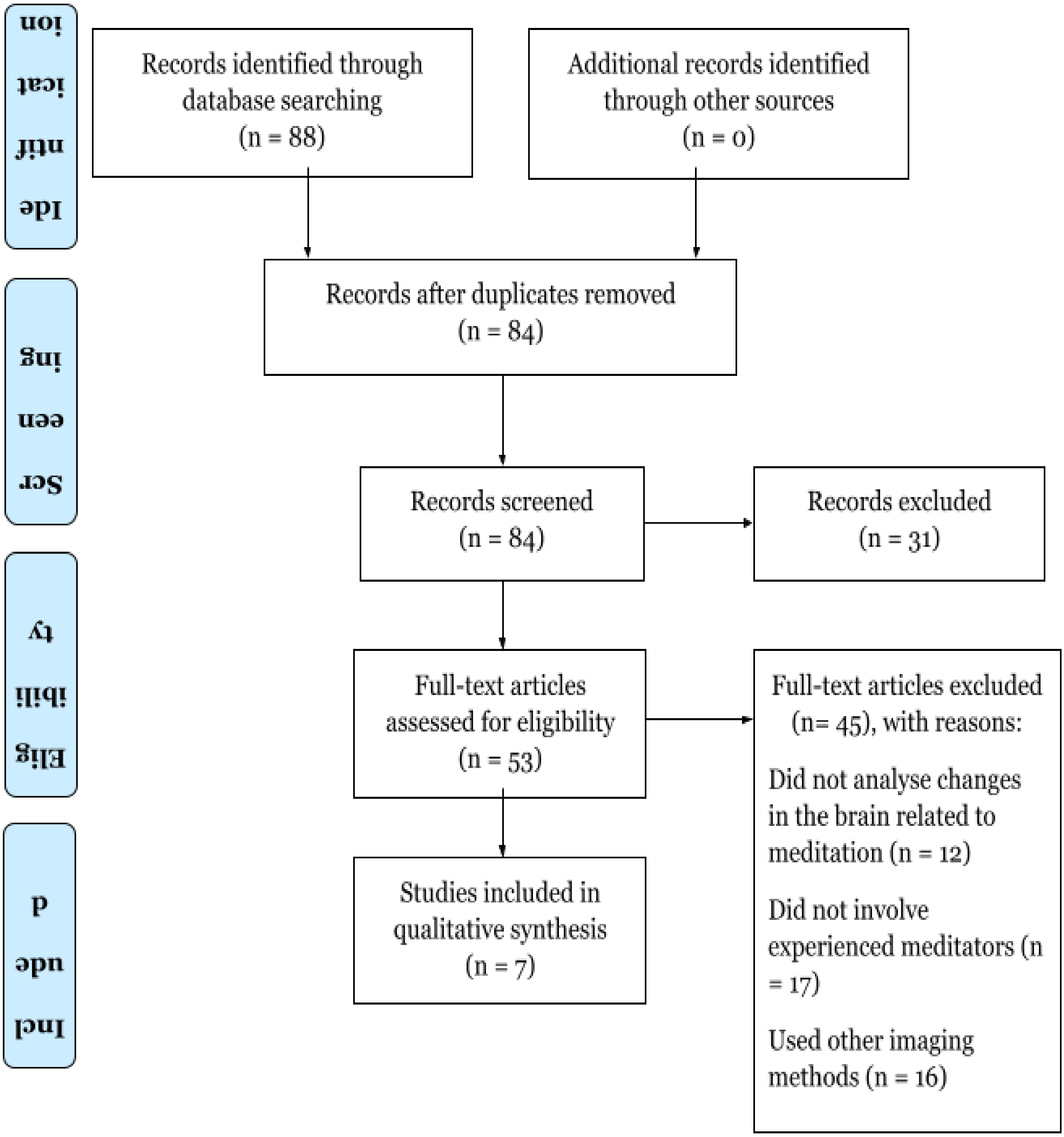
The inclusion criteria were the following: 1) only published and peer-reviewed empirical studies, 2) studies that included experienced meditation practitioners, 3) studies that used neuroimaging methods such as functional magnetic resonance imaging (fMRI), Magnetic Resonance Imaging (MRI) and/or Electroencephalography (EEG) 4) only healthy adult participants, 6) only studies published in English. Exclusion criteria were 1) studies involving only novice-practitioners 2) methods using other imaging techniques than fMRI, MRI or EEG, 3) studies that did not analyze changes in the brain related to meditation.

Data extraction

This systematic review will present data from seven different studies that are measuring changes in the brain concerning the practice of meditation. All studies include healthy, experienced adult meditators. The following data was extracted: article, sample size, age range, neuroimaging method (fMRI, MRI or EEG), meditation form and main findings. The measuring outcomes were generated from functional and structural brain differences in experienced meditators and non-meditators.

Figure 1.

PRISMA 2009 Flow Diagram



Note. PRISMA 2009 Flow Diagram: standard flow diagram used to illustrate the literature search process. Citation: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and

MetaAnalyses: The PRISMA Statement. PLoS Med 6(7): e1000097.
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Results

Study Characteristics

This review aims to analyze seven different articles, where a total of 254 participants were included. Sample sizes ranged from 20-60, and ages ranged from 21-70 across the studies (see Table 1). In all of the seven studies, expert meditators with at least three years of meditation experience were compared with controls that were non-meditators or novices. All subjects included in the studies were healthy, with no background of neurological or psychiatric disorders.

Different meditation forms were used across the articles. Two studies involved mindfulness meditation (Berkovich-Ohana et al., 2016; Vestergaard-Poulsen et al., 2009), three studies used Shamatha, Zen, and Vipassana meditation (Guidotti et al., 2021; Luders et al., 2009; Luders et al., 2012), one used Sahaja Yoga meditation (Hernandez et al., 2020) and one study (Pagnoni & Cekic 2007) used Zen meditation. Vestergaard-Poulsen et al. (2009) also included Loving-kindness meditation (LKM). All studies involved only fMRI and MRI of which two used fMRI (Berkovich-Ohana et al., 2016; Guidotti et al., 2021) and five used MRI (Hernandez et al., 2020; Luders et al., 2009; Luders et al., 2012; Pagnoni & Cekic, 2007; Vestergaard-Poulsen et al., 2009). All four MRI studies additionally used voxel-based morphometry to induce anatomical brain images of both the whole brain and regions of interest. In regard to mediation tasks, one of the studies (Berkovich-Ohana et al., 2016) used a visual recognition-memory task (VRM), and one used the task of rapid visual information processing (Pagnoni & Cekic, 2007). Two studies gave verbal and guided meditation instructions (Guidotti et al., 2021; Vestergaard-Poulsen et al., 2009), and three articles did not provide any particular instructions (Hernandez et al., 2020; Luders et al., 2009; Luders et al., 2012).

Functional Correlates of Meditation

Brain activity and changes in functional connectivity in different regions of the brain have been linked to various kinds of mediation practices (Brewer et al., 2011). Berkovich-Ohana et al. (2016) intended to test the “spontaneous trait reactivation” (STR) hypothesis, in which they assumed that resting-state activity patterns would be detected in experienced meditators. More specifically, the researchers hypothesized to find changes in functional connectivity during spontaneous resting-state fluctuations in meditators. To explore any possible correlation between the practice of meditation and changes in resting-state fluctuations, fMRI scannings were performed on a total of 36 mindfulness meditation practitioners, of which 18 were experienced meditators. The participants were asked to complete VRM in which the data was used to compare the brain activity with the resting state. The VRM task included visual stimuli in form of faces, buildings, common man-made objects, and geometric figures. To ensure that the participants did not fall asleep or meditate during the resting state they were interviewed while in the scanner. The researchers found that, during resting state, meditators demonstrated a larger scale of spontaneous fluctuations in the visual cortex (including bilateral posterior fusiform and lateral occipital cortices) compared to the control group. The Opposite effect was displayed in the DMN regions (more specifically the bilateral precuneus (Prc) and inferior parietal lobule (IPL)), where the result showed a significant reduction in fluctuation amplitude in meditators in comparison to controls. Moreover, the experienced meditation group demonstrated heightened visual cortex responsivity and weaker negative responses in DMN regions. Meditation practitioners further performed faster in the VRM task than the control group. Based on the findings, the STR hypothesis was supported in Berkovich-Ohana et al.'s study (2016).

Functional connectivity patterns in the brain have been associated with focused attention (FA) and open monitoring (OM) mediation in long-term practitioners as well as novices. Guidotti et al. (2021) conducted an fMRI study on twelve Theravada Buddhist monks that had 8-24 years of meditation experience in both FA and OM practices in the forms of Vipassana (FA) and Shamatha (OM) meditation. A control group consisting of 10 novice meditators was used for comparison. The researchers aimed to investigate the impact of FA and OM mediation expertise on functional connectivity within and between large-scale brain networks. Moreover, the study examined whether meditation expertise and age can be predicted from the patterns of functional connectivity in both forms of meditation. More specifically, the researcher hypothesized that years of mediation practice and age can be predicted by the patterns of functional connectivity in significant brain regions associated with the Vipassana and Shamatha meditation. Further, it was hypothesized that regarding FA meditation, connectivity patterns would be associated with nodes engaged in focusing, sustaining, and monitoring attention. On the other hand, connectivity patterns in OM mediation would involve nodes linked to interoception, cognitive and affective monitoring, and regulation. With the mentioned hypotheses, the researcher's aim in broad terms was to explore if FA and OM mediation affect neuroplasticity. To conduct the experiment, verbal instructions were given to the participants before each meditation type and resting state. The total session time was 57 minutes composed of three-time blocks: 6 minutes of FA and 6 min of OM meditation with 3 minutes of rest after each meditation form. To ensure that the participants were performing both FA and OM meditation forms correctly, they were instructed to fill in self-reports after the session. The two variables (meditation expertise and age) were measured using fMRI and BOLD-signal imaging to generate whole-brain images. The findings of Guidotti and colleagues (2021) show that fMRI functional connectivity data observed in meditation states can predict meditation expertise and age. In association with expertise in FA meditation, an increase in connectivity was observed between the left intraparietal sulcus (IPS), angular gyrus (AngG), and the anterior cingulate cortex (ACC), brain areas that take part in top-down attention and attentional control. Additionally, meditation expertise was associated with a negative correlation in connections between the posterior cingulate cortex (PCC) and the left occipital gyrus, which are key parts of the default mode network (DMN). The researchers further found that increased OM meditation experience was associated with activity in brain nodes in the Language Network such as the left angular gyrus (LAG) and left middle temporal gyrus. Regarding age prediction, the study found that the caudate-thalamus connections within the basal ganglia network were most significant. Guidotti et al. (2021) revealed in their study that in experienced meditators of FA and OM forms, functional connectivity patterns within and between different brain networks can predict the level of meditation expertise and age.

Structural Correlates of Meditation

Previous studies have demonstrated that larger gray matter volume (GMV) is associated with long-term meditation practices (Froeliger et al., 2012). Hernandez et al. (2020) conducted a study on 23 experienced meditators of Sahaja Yoga Meditation (SYM), and 23 healthy non-meditators for comparison. SYM has shown health benefits in mental deficits such as depression, stress, anxiety, and attention-deficit/hyperactivity disorder. In their study, the researchers aimed to investigate GMV in brain areas along with regional differences in experienced meditators versus non-meditators. All participants were matched in age, sex and education level. To conduct the study, an MRI scanner was used for obtaining whole brain images. Voxel-based morphometry (VBM), a common technique for measuring GMV by means of MRI scans was used to measure GMV in regions of interest. The researchers applied two different methods for analyzing the volume in different brain regions: 16 lobes area subdivision and 116 automated anatomical labelling (AAL) area subdivision. Out of the 16 lobes area subdivision, four showed a significantly larger GMV in long-term meditators compared to controls, including the right temporal, right frontal, right brainstem and left frontal. In the 116 AAL area subdivision, 11 demonstrated significantly larger GMV in meditators compared to non-meditators. The six areas in the AAL area that showed the largest GMV differences included the middle and inferior temporal lobe, inferior and orbital frontal cortices, and in para- and precentral lobes. These areas are essential for higher cognitive functions, emotion regulation, working memory, and sustained attention. Moreover, a difference was detected in meditators in the brain areas inferior and orbitofrontal cortex, middle temporal lobe, precentral and paracentral gyrus, and brainstem. The most significant differences of GMV were found in the right hemisphere of the brain in both subdivisions. The largest area in AAL was the right middle temporal gyrus, which in previous studies has been associated with subjective feelings that come with religious and spiritual practices. Notably, the largest GMV differences were detected in frontal and temporal brain areas in the right hemisphere, which are regions known to be associated with attention and emotional control (Hernandez et al., 2020).

Luders et al. (2009) aimed in their study to explore the associations between meditation and brain activity, and its underlying structural correlates. A total of 44 healthy subjects participated, of which 22 were long-term meditators with at least five years of experience, and 22 non-meditators were included in the control group. Different types of meditations were used for the purpose to uncover the underlying neural correlates of long-term practice independent of one particular practice. The main meditation forms included Zen, Shamatha, and Vipassana mediation. The researchers used high-resolution MRI data to examine the connection between meditation and brain anatomy. Possible links between specific brain structures (global, regional, and local) were identified with the neuroimaging technique voxel-based morphometry (VBM). Based on previous positive correlations between meditation experience and brain structure, the researcher split meditators into two groups and conducted two different analyzes. One group included participants with less than 20 years of meditation experience (n=13) and the other with more than 20 years of experience (n=9). Additionally, the researcher analyzed meditators versus controls comparing them while co-varying for age. The findings from the local gray matter volumes showed significantly increased gray matter in meditators compared to controls in the right orbito-frontal cortex, specifically inferior and middle frontal gyrus, and right thalamus. The same distinction was found in the co-varying age analysis. Regarding the global volume, no difference was detected between meditators and controls. Nor was any difference shown in the following regions of interest left inferior temporal gyrus, right insula, right superior frontal gyrus, and right middle frontal gyrus. Nevertheless, larger volumes of the right hippocampus were found in meditators compared to controls. With respect to the relationships between local gray matter and number of meditation years, no significant effect was found between the groups. The main finding that the researchers discovered was increased gray matter in meditators in the orbito-frontal cortex. Furthermore, an increase of gray matter was demonstrated within the thalamus in meditators. The thalamus engages as a regulator of the flow of sensory information and has been linked to a decrease of sensory input in the posterior superior parietal lobule, which Luders et al. (2009) suggest may account to an enhanced sense of focus.

One area that recent studies have linked to long-term practice of meditation is the corpus callosum, the largest fiber structure that interconnects the two brain hemispheres (Luders et al., 2012). In their study, Luders et al. (2012) explore the callosal features in association with meditation, using 30 long-term meditators that had a range of 5 to 46 years of experience, and 30 non-meditating controls. The meditators practiced different types of meditation forms including Shamatha, Vipassana, and Zen meditation. Based on previous findings, the authors hypothesized larger callosal measures in meditators compared to controls. The researchers combined diffusion tensor imaging (DTI) and MRI for image acquisition and for measuring the callosal thickness. Both global and local callosal measures were conducted. The final main results demonstrated larger callosal thickness, specifically in anterior sections in meditators compared to controls. Regarding the global callosal measures, no significant difference was found between the groups. In the local callosal measure, however, thicker corpora callosa between anterior midbody and anterior third was detected in meditators in comparison to the control group. These findings reflect that the impact of meditation practice showed a stronger outcome in the local parts of callosal features.

Rooted in Buddhism culture, one meditation form that has increased its awareness in modern psychology and neuroscience is Zen meditation. Prior studies have shown a link between long-term practice of Zen meditation and plasticity in the brain. Pagonini & Cekie (2007) conducted an experiment to explore the possible effect of the normal age-related decline of cerebral gray matter volume and attentional performance linked to long-term Zen meditation practice. A total of 26 healthy participants were included in the study, where 13 were regular Zen meditation practitioners with at least 3 years' experience and 13 non-meditating controls. A computerized sustained attention task was utilized where the participants individually were instructed to observe a stream of fast appearing digits on a computer screen and target three specific sequences. For measuring cerebral gray matter volume, the researcher used Voxel-based morphometry to induce MRI anatomical brain images. The results in the age-related decline rate of cerebral gray matter volume revealed a difference in the putamen between the mediation group and controls. Additionally, a marginal difference was noticed among meditators and controls in the correlation of age and cortical thickness of prefrontal cortex. The findings hence showed a decreased rate of decline with age in both global and local gray matter volume in meditators, which the authors suggest may indicate the engagement of neuroprotection. With respect to gray matter volume and attentional performance with age, a significant negative correlation was observed in control subjects, which was not observed in meditators. The most notable area that Zen meditation practice had an impact on regarding gray matter volume was in the putamen, a region involved in attentional processing. The authors suggest that the observed anatomical differences in meditators and controls may be linked to cognitive processes that comes with long-term meditation practice, such as attentional, postural control and executive functions. Pagonini & Cekie (2007) suggest that the cognitive decline associated with normal aging may be reduced by the continuous practice of Zen meditation.

The main element in most meditation forms is focusing the attention on the breath. Vestergaard-Poulsen et al. (2009) aim to investigate how gray matter density in the lower brainstem, which is an important part of the brain that helps regulate the breath, is associated with long-term mediation. To perform their study, the researchers used voxel-based morphometry of whole-brain (including the lower brainstem) MRI in a total of 20 subjects. The participants were equally parted into two groups, one control group with no prior mediation experience, and one that included long-term meditators with an average of 16.5 years of experience. The meditation practices that the participants performed involved Concentrative practices (such as sustaining attention upon mental content or bodily sensations), and Open awareness practices (no specific focus). The main elements included LKM and mindfulness meditation. Based on previous studies that demonstrated structural changes in the brain linked to meditation, the researcher hypothesized similar findings would be observed in the brainstem. More specifically, gray matter density and volume were measured and compared in meditators and controls to identify potential differences. The results showed a significantly increased gray matter density, but no volume difference in meditators compared to controls in the lower part of the brainstem, also known as the medulla oblongata. Moreover, structural difference was observed linked to long-term meditation in the anterior cerebellum (bilaterally), the left superior and inferior frontal gyrus, and the left fusiform gyrus. Largest difference was detected in the dorsal part of the brainstem, including the solitary tract nucleus and the dorsal motor nucleus of vagus, which are known as brain areas involved with the autonomic nerve system. Altogether, Vestergaard-Poulsen et al. (2009) point out their findings to be noteworthy, given the indication of long-term mediation practice being associated with structural differences in the lower brainstem.

Table 1

Study Characteristics

Article	Sample Size	Age Range	Meditation Experience	Neuroimaging Method	Meditation Form	Main Findings (In Meditators)
Berkovich-Ohana et al. (2016)	N = 36	33–52	940–27,400 h	fMRI	Mindfulness-meditation	Changes in the DMN and visual cortex
Guidotti et al. (2021)	N = 22	22–60	8–24 years	fMRI	Samatha and Vipassana	Changes in FC patterns in: IPS, AngG, and ACC
Hernandez et al. (2020)	N = 46	21–63	5+ years	MRI	Sahaja Yoga Meditation	Larger GMV in right hemisphere; MTG.R
Luders et al. (2009)	N = 44	30-70	5-46 years	MRI	Zen, Samatha and Vipassana	Larger hippocampal and frontal GMV
Luders et al. (2012)	N = 60	24–64	5-46 years	MRI	Zen, Samatha and Vipassana	Thicker callosal regions
Pagnoni & Cekic (2007)	N = 26	27–44	3+ years	MRI	Zen meditation	Age-related decline rate of cerebral GMV in the putamen
Vestergaard-Poulsen et al. (2009)		49–61	14-31 years	MRI		

	N = 20		Mindfulness and Loving-kindness	Increased gray matter density in brain stem

Note. Abbreviations: fMRI = functional magnetic resonance imaging. MRI = magnetic resonance imaging. FC = functional connectivity. DMN = default mode network. IPS = intraparietal sulcus. AngG = angular gyrus. ACC = anterior cingulate cortex. GMV = gray matter volume. MTG.R = right middle temporal gurys

Discussion

This systematic review aims to investigate the underlying functional and structural differences in brain mechanisms between long-term meditators and non-meditators, involving different meditation forms. A total of seven articles matched with the inclusion criteria, of which all found significant changes in the brain in meditators. The following meditation forms were included in the review: Mindfulness meditation, Samatha meditation, Vipassana meditation, Zen meditation, Sahaja Yoga meditation, and Loving Kindness meditation. All forms have the common feature of focusing on the breath and/or a mantra.

Long-term meditation practice has amongst other benefits, been shown to ease depressive, anxiety, and stress symptoms, and to increase attentional performance (Garrison et al., 2014). Based on the hypothesis of “spontaneous trait reactivation” by a prior study (Harmelech & Malach, 2013), Berkovich-Ohana et al. (2016) conducted their experiment to explore if any spontaneous fluctuations would be observed in long-term meditators of mindfulness. The final results supported the hypothesis with demonstrated enhanced spontaneous fluctuations in the visual cortex, and by contrast reduced in DMN in meditators compared to controls. The findings that Berkovich-Ohana et al. (2016) made resonate with previous fMRI studies where reduced brain activity in the DMN has been linked to long-term meditation practices, especially mindfulness based (Marchand, 2014). It is suggested that the decreased activity in DMN observed in meditators has to do with the involved brain areas (the medial prefrontal cortex, posterior cingulate cortex, and left temporoparietal junction) that are accountable for attention and emotion regulation, mind-wandering, and self-referential thoughts. Similar findings were demonstrated in the more recent fMRI study by Guidotti et al. (2021). In their experiment, additionally, to the observed reduced activity in DMN, patterns were found of functional activity in experienced Shamata and Vipassana meditators in the IPS, AngG, and ACC (brain regions known to be involved with attentional control). The mentioned findings in functional connectivity can justify that during FA meditation, a decrease of spontaneous thoughts and mental images can occur. A high correlation of functional connectivity was also revealed between the left and right hippocampus, the main brain area involved in integrating episodic memories, information, and emotional processing. (Guidotti et al., 2021).

Five of the studies (Hernandez et al., 2020; Luders et al., 2009; Luders et al., 2012; Pagnoni & Cekic, 2007; Vestergaard-Poulsen et al., 2009) investigated structural changes in meditators compared to non-meditators using MRI and VBM for measuring GMV in whole-brain and/or regions of interest. Larger GMV has in previous studies been demonstrated to be associated with long-term meditation practices (Froeliger et al., 2012). Luders et al. (2009) and Pagnoni & Cekic (2007) both found larger GMV in experienced meditators who practiced Zen meditation, whereas Hernandez et al. (2020) conducted their study on Sahaja Yoga practitioners. The main brain areas where larger GMV was detected in all three studies included the middle and inferior temporal lobe, and inferior and orbital frontal cortices. The mentioned areas have previously been shown to be involved with emotion self-regulation, specifically reappraising negative emotional stimuli (Kang et al., 2012). Additionally, Luders et al. (2009) observed in meditators practicing Zen, Shamatha or Vipassana, a greater GMV in the hippocampal areas, a further brain region resonating with studies to be associated with long-term meditation (Wells et a., 2013). The detected enlarged gray matter in the right hippocampus is suggested accountable for the abilities to cultivate positive emotions and maintain emotional stability that is commonly observed in meditators (Davidson et al., 2000). Luders et al. (2012) based their experiment on prior studies (Luders et al., 2011a, Tang et al., 2010) that have detected callosal differences in experienced meditators. Their final results were in agreement with previous findings, indicating thicker callosal regions in long-term meditators. Research suggests that thicker callosal regions in meditators might indicate more fibers crossing the corpus callosum and that thicker callosal regions may signal increased interhemispheric connectivity. This allows for enhanced integration of information between the two hemispheres (Luders et al., 2012). Further, Vestergaard-Poulsen et al. (2009) found increased gray matter density in the brainstem, more specifically in the dorsal parts in experienced mindfulness and loving-kindness meditators. In most meditation forms, including mindfulness, the main focus is the breath (Kabat-Zinn, 2009). Prior studies have shown meditation to be linked with reduced breathing and heart rate (features of the autonomous control centers), which may justify the findings of gray matter density in the brainstem.

Taken together, both structural and functional connectivity was detected in meditators compared to non-meditators. Distinctions were observed in different brain regions depending on the imaging method and what brain regions were being measured. Some of the studies were more specific in what part of the brain was being measured. For instance, Luders et al. 2012 focused on the structural measures around the callosal areas, whilst Vestergaard-Poulsen et al. (2009) centered their study on the brainstem.

Limitations and Future Research

Several methodological limitations exist within the studies included in this review. Regarding the meditation forms that were included in the studies, focusing on the breath was one of the main aspects. However, some of the studies (Guidotti et al., 2021; Luders et al., 2009; Luders et al., 2012; Vestergaard-Poulsen et al., 2009) used more than one meditation form in their measures. The use of different meditation forms may interfere with the consistency of the results, depending on to what extent the practices differ. By focusing on one specific meditation style, future research may discover greater group differences. Another limitation that seems to be common in meditation studies involving experience meditators, is the number of participants. The highest total of subjects in this review was N = 60 (Luders et al., 2012) and the lowest N = 20 (Vestergaard-Poulsen et al., 2009) of which only half of the participants were experienced meditators. Similarly, Luders et al. (2012) note the importance of acknowledging the age gap between the participants. In their study, for instance, the youngest participant was 24 whereas the oldest was 64. In later adulthood, the white matter in the brain goes through significant changes due to fiber loss and demyelination, which Luders et al. (2020) point out could affect the final measures. Future studies should consider a more limited age gap in subjects.

Moreover, Vestergaard-Poulsen et al. (2009) argue that other possible reasons for the observed brain changes in long-term meditators cannot be ruled out. For example, it cannot be assured that the differences are not caused by a preference for engaging in meditation and, not as a consequence of the engagement. Further, other possible causes can also be a reason for the observed GMV differences between meditators and non-meditators, such as lifestyle and personality (Hernandez et al., 2020). To better determine the cause of structural brain changes in long-term meditators, future research may benefit from conducting longitudinal studies.

Ethical and Societal Aspects

This systematic review includes seven studies of which all were approved by an ethics review board. All participants included in the studies were healthy without any neurological or psychological illnesses and were asked for informed consent before participating. With respect to the society level, studying neural correlates of meditation may neglect individual and subjective experiences, considering the objective measures. Several psychological health benefits have been proven in healthy individuals that regularly engage in meditation practices. Given that only healthy participants were included in all studies, they were at no risk, and may preferably experience boosted subjective well-being.

Conclusion

The aim of this thesis was to explore the underlying functional and structural differences in brain mechanisms between long-term meditators and non-meditators, involving different meditation forms. A clear link regarding brain activation in the various mediation types included in the studies was complex to find due to the individual studies using different methods. Nevertheless, some consistency was found across the studies. The outcomes of this review showed that brain regions known to be involved in higher cognitive abilities such as emotional regulation, attentional control, memory, and executive functions appear to be common findings related to long-term meditation throughout the studies. These include areas such as the prefrontal cortex, the DMN, ACC, and hippocampus. Additionally, thicker callosal areas and increased gray matter density were found in long-term meditators compared to non-meditators. Altogether, the findings indicate that both functional and structural alterations in the brain can be linked to meditation. Nevertheless, further research needs to be conducted with methodological issues considered. A better understanding of the neural correlates associated with meditation experience may bring a deeper insight into the phenomenon of consciousness, neuroplasticity, and the suggested health benefits that come with meditation.

Word count = 6402

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