

# Does Neuroimaging Provide Evidence of Meditation-Mediated Neuroplasticity?

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**Abstract** Results of recent magnetic resonance imaging studies suggest that meditation may be associated with region-specific structural neuroplasticity. To test the hypothesis that meditation-related brain function predicts site-specific structural changes in meditators, we conducted two meta-analyses: one of studies localizing brain activity during meditation, and a second of studies measuring differences in brain structure between meditators and non-meditators. Activation Likelihood Estimation (ALE) meta-analysis of five studies measuring brain activation during meditation revealed the greatest clusters of activity to be in the left frontal cortex and left precuneus. ALE of four studies measuring the differences in brain structure between meditators and controls revealed that meditators tended to have greater brain volume in the left inferior temporal gyrus. Thus, brain activity during meditation did not predict region-specific structural differences between meditators and non-meditators. This finding may reflect recognized limitations in neuroimaging methodology rather than the refutability of the hypothesis itself. Future efforts aimed at understanding the relationship between brain activity and structural changes in the brain should focus on improving neuroimaging experimental design and incorporating evidence from other branches of neurocognitive science. Progress in these areas promises to elucidate the connection between mind-body practices, and brain structure and function.

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## Introduction

Recent magnetic resonance imaging (MRI) studies demonstrate that training in some skills such as music, language, and spatial navigation is associated with increased gray matter in regions relevant to the learned task (Gaser and Schlaug 2003; Machelli et al. 2004; Maguire et al. 2000). Intensive training in juggling, for example, leads to increased gray matter in regions known to be important in perceptual-motor coordination (Draganski et al. 2004). In addition, increases in gray matter occur in less time than previously recognized. A 2007 study aimed at defining the usage dependent time scale of structural changes found that architectural alterations in the brain were detectable within a week of the intervention (May et al. 2007).

Meditation is a mind-body practice which originated in ancient religious and spiritual traditions. In Western culture, its secular clinical application falls under the rubric of complementary and alternative medicine (CAM). Meditation incorporates a diverse array of practices including various combinations of breathing, mantra recitation, focused attention, and practices related to spiritual beliefs. It has been extensively studied as a method of relaxation and has been associated with numerous physiological benefits (Benson 1984; Davidson et al. 2003; Kabat-Zinn et al. 1992, 1998). It has also been used as a method of fostering attention and emotional self-regulation (Jha et al. 2007; Ospina et al. 2007).

Functional magnetic imaging studies of meditation demonstrate that meditation is associated with brain activation in a number of cortical and sub-cortical regions including the frontal and parietal cortices, known to be important in the mental process of attention, and the insula, known to be important in emotional regulation (Lazar et al. 2000; Holzel et al. 2007). Some authors have found structural differences between the brains of meditators and non-meditator controls and speculate that differences are due to a meditation-associated training effect and structural neuroplasticity (Lazar et al. 2005; Holzel et al. 2008; Luders et al. 2009).

While common areas of activation have been identified among neuroimaging studies exploring the brain during meditation, there is some inconsistency across studies. Moreover, studies exploring differences in the brain structure of meditators versus controls fail to demonstrate consistent differences between the two groups.

Meta-analysis, specifically coordinate-based meta-analysis (CBMA), offers a method of pooling neuroimaging study results, and thus can be used to summarize and clarify these two sub-categories of MRI studies (i.e., studies of brain activation associated with meditation, and studies measuring structural differences between meditators and non-meditators). Results of such meta-analyses are amenable to comparison and would help determine if brain activity during meditation predicts differential brain structure between meditators and non-meditators. To date, no such studies have been published.

To explore the hypothesis that meditation mediates region-specific structural neuroplasticity, we reviewed the literature to identify fMRI studies measuring brain activity during meditation, and performed Activation Likelihood Estimation (ALE) meta-analysis of the pooled coordinates. Studies measuring brain structure in

meditators were considered separately and coordinates were pooled in a second ALE meta-analysis (Laird et al. 2005; Turkeltaub et al. 2002). We then compared the results of these meta-analyses to see if brain activation predicted region-specific structural differences between meditators and non-meditators.

## Methods

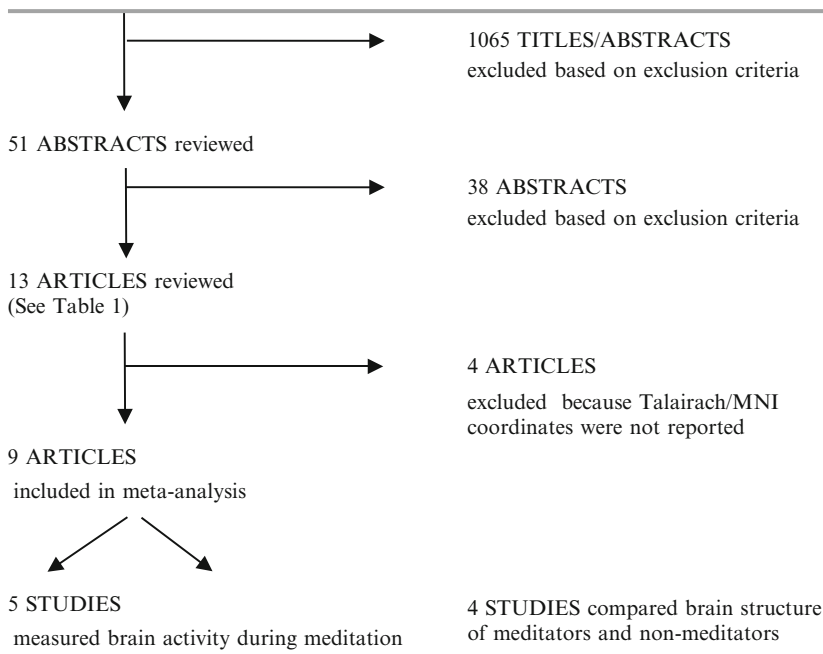
Two independent reviewers completed a multilevel systematic literature search. Using the key words “meditation AND mri”, databases (PubMed, EMBASE, Cinahl, Cochrane Database for Systematic Reviews, and PsychINFO) were searched for MRI studies of meditation published since 2000. (Because “yoga” is synonymous to “meditation” in Cinahl, the key words “yoga AND mri” were also used to search this database). Our gray literature search included searches of metaRegister of Controlled Trials, Cochrane Central Register of Controlled Trials, and Google Scholar. References of identified studies were hand searched.

For a study to be included in our review, it had to meet the following inclusion/exclusion criteria: (1) the study had to be an interventional or observational study; case reports, case series, letters, and editorials were excluded; (2) the study had to use magnetic resonance imaging to measure neural activity during meditation (state), or to measure brain structure of individuals with meditation experience versus controls (trait); (3) studies measuring differential responses to stimuli (pain, sound, etc.) during meditation versus rest, or in meditators versus non-meditators were not included in this review. In instances where studies focused primarily on stimulus–response but also included information on activation during meditation, pertinent information was extracted from the study and included in our review; (4) studies had to be published between 2000 and 2009 (2000 documents the first study of this kind); and (5) while subject description was required, there was no restriction on the study population. Disagreements between reviewers with regard to inclusion/exclusion of individual studies were resolved by consensus.

Activation Likelihood Estimation (ALE) meta-analysis was performed using GingerALE v1.1 software and the following parameters: a full-width half maximum (FWHM) of 10 mm, permutations of 5000, q-value of 0.05, and a minimum cluster size of 100 mm<sup>3</sup> (Laird et al. 2005). Once the thresholded ALE map was generated using GingerALE v1.1, an anatomical underlay (in Talairach space) was downloaded and images were generated using Multi-Image Analysis Graphical User Interface (Mango) (Kochunov et al. 2002) (Lancaster and Martinez Accessed 24 May 2009).

## Results

Using the inclusion criteria outlined, a total of 1,116 titles/abstracts were reviewed and 1,065 were excluded. From the remaining 51 abstracts, the full articles were reviewed in more detail and 13 articles were considered for inclusion. Four



**Fig. 1** Study selection flow chart

studies were excluded from meta-analysis because Montreal Neurologic Institute (MNI) coordinates were not reported. This resulted in nine studies eligible for meta-analysis, five were studies of brain activation during meditation, and four were studies comparing brain structure between meditators and non-meditators (see Fig. 1).

Systematic review of the 13 included studies, which used MRI to study meditation/meditators, revealed that such studies are generally small, ranging in size from 5 subjects to 44 subjects. Most studies included controls. However, two of the studies measuring brain activation during meditation used the non-meditative state as the control. The age of participants ranged from 22 years to 71 years (mean 34–53 years). Overall, there was a preponderance of males studied. In the 11 of 13 experiments where both sexes were represented, investigators took care to ensure that equal numbers of each sex were included in the experimental and control groups. Most participants were right handed. Handedness was matched in studies reviewed. The type of meditation practiced and the duration of practice varied between studies (2–46 years). While attention was given to meditation type and the possible impact that this might have on MRI results, from the perspective of neuroimaging, meaningful subcategories have yet to be delineated and meditation type was not considered here (i.e., all meditation types were included in meta-analysis).

In addition to the potential covariates listed in Table 1, inconsistently reported covariates include ethnicity/race, and level of education. Very few studies reported on the general health of participants and controls. Only 1 out of 13 studies included information about medication use. With regard to image acquisition and statistical analysis, the majority of studies reviewed included information about scanners and software utilized. Only studies which reported statistically significant coordinates were included in meta-analysis (see Table 1).

## Brain Activation During Meditation

Two of the studies reviewed measured brain activation during meditation as compared to rest (Shimomura et al. 2008; Lazar et al. 2000); these studies revealed consistently greater activation in the frontal cortex during meditation. The parietal and cingulate cortices were also activated during meditation, but this finding was less consistent. (Lazar et al.) found additional areas of activation in the midbrain and putamen (Lazar et al. 2000).

Three studies measured the difference in brain activity during meditation between meditators and non-meditators. (Lutz et al. 2008); (Brefczynski-Lewis et al. 2007); and (Hölzel et al. 2007) found consistently greater activation during meditation in meditators versus controls in the frontal, parietal, occipital/temporal cortices and hippocampus and, less consistently, greater activation in the cingulate cortex and other subcortical regions (Lutz et al. 2008; Brefczynski-Lewis et al. 2007; Holzel et al. 2007). These authors infer that activation of specific brain areas is related to attention and emotional regulation and that the differential activation between meditators and non-meditators represents a measurable training effect.

Activation Likelihood meta-analysis of studies measuring brain activation during meditation revealed the greatest clusters of activity to be in the left superior frontal gyrus, left medial frontal gyrus, left middle frontal gyrus, and the left precuneus. Areas reported to demonstrate activation in more than one of the individual studies but which did not result in significant clusters of activity on ALE include the cingulate and insula (see Table 2, Figs. 2 and 3). (See Appendix 1 for details of extracted coordinates.)

## Differences in Brain Structure Between Meditators and Controls

Pagnoni and Cekic (2007) found that the total gray matter volume showed a marginally significant negative correlation with age in the control group but not the meditators. Meditators showed significantly less age-related gray matter volume decline in the left putamen than controls (Pagnoni Gand Cekic 2007).

**Table 1** Magnetic resonance imaging studies meeting inclusion criteria for systematic review

	Author	Year	Meditators/controls	Age range [mean]	Sex	Type of meditation	Duration of practice (mean)	Meta-analysis included/excluded (reason)
Structural differences between meditators and non-meditators	Luders et al.	2009	22/22	30–71 years [53 years]	9 male/13 female	Varied (Vipassana, Zenen, Samatha, others)	5–46 years (24 years)	Included
	Lazar et al.	2005	20/15	[38 years]	13 male/7 female	Buddhist	9 ± 7 years	Excluded (MNI coordinates not available)
	Hölzel et al.	2008	20/20	[34 years]	16 male/4 female	Vipassana	2–16 years (9 years)	Included
	Vestergaard-Poulsen et al.	2009	10/10	[55 years]	6 male/4 female	Buddhist	14–31 years (16 years)	Included
	Pagnoni et al.	2007	13/13	[37 years]	10 male/3 female	Buddhist	> 3 years	Included

Activation during meditation	Shimomura et al.	2008	8/0	[41 years]	8 male/0 female	Buddhist	> 10 years	Included
	Brefczynski-Lewis et al.	2007	14 expert meditators/16 novice meditators/11 incentivized novice meditators	[47 years]	Not given	Buddhist	10,000–54,000 total hours	Included
	Hölzel et al.	2007	15/15	[34 years]	12 male/3 female	Vipassana	2–16 years (8 years)	Included
	Lazar et al.	2000	5/0	22–45 years	4 male/1 female	Kundalini	> 4 years	Included
	Short et al.	2007	13/0	18–60 years [43 years]	5 male/8 female	Varied	> 4 years	Excluded (MNI coordinates not available)
	Lutz et al.	2008	16/16	29–64 years	14 male/2 female	Buddhist	(45 years)	Included
	Khushu et al.	2005	11/0	32–65	10 male/1 female	Brahmakumari Rajayoga	> 3 years	Excluded (MNI coordinates not available)
	Ritskes et al.	2003	11/0	32–62	8 male/3 female	Zen	15–25 years (8 years)	Excluded (MNI coordinates not available)

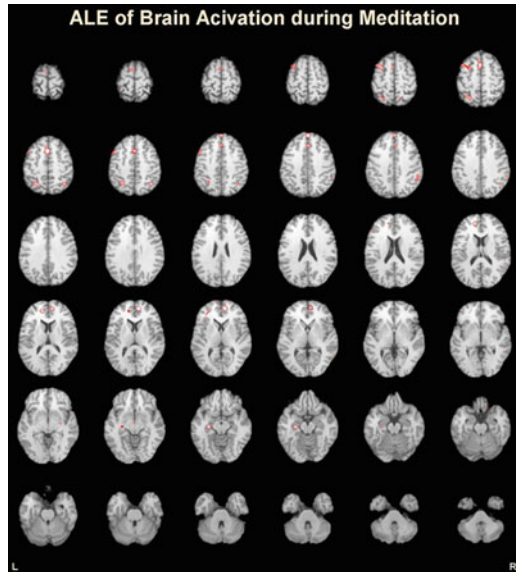
**Table 2** ALE meta-analysis: brain activation during meditation

	Author	Year	Meditators/controls	Age range [mean]	Sex	Type of meditation	Duration of practice (mean)	Meta-analysis included/excluded (reason)
Structural differences between meditators and non-meditators	Luders et al.	2009	22/22	30–71 years [53 years]	9 male/13 female	Varied (Vipassana, Zen, Samatha, others)	5–46 years (24 years)	Included
	Lazar et al.	2005	20/15	[38 years]	13 male/7 female	Buddhist	9 ± 7 years	Excluded (MNI coordinates not available)
	Hölzel et al.	2008	20/20	[34 years]	16 male/4 female	Vipassana	2–16 years (9 years)	Included
	Vestergaard-Poulsen et al.	2009	10/10	[55 years]	6 male/4 female	Buddhist	14–31 years (16 years)	Included
	Pagnoni et al.	2007	13/13	[37 years]	10 male/3 female	Buddhist	> 3 years	Included

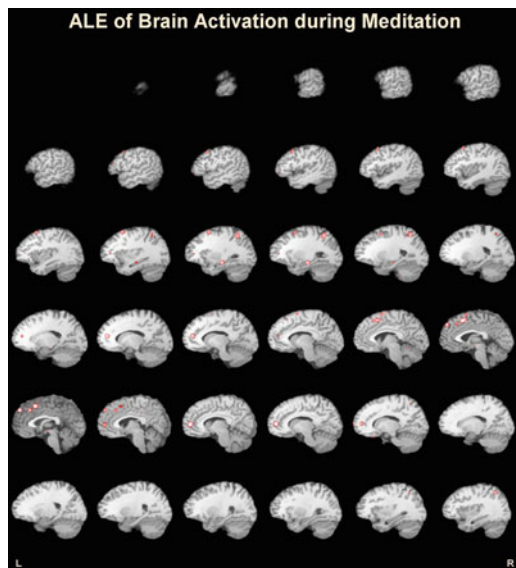


Activation during meditation	Shimomura et al.	2008	8/0	[41 years]	8 male/0 female	Buddhist	> 10 years	Included
	Brefczynski-Lewis et al.	2007	14 expert meditators/16 novice meditators/11 incentivized novice meditators	[47 years]	Not given	Buddhist	10,000–54,000 total hours	Included
	Hölzel et al.	2007	15/15	[34 years]	12 male/3 female	Vipassana	2–16 years (8 years)	Included
	Lazar et al.	2000	5/0	22–45 years	4 male/1 female	Kundalini	> 4 years	Included
	Short et al.	2007	13/0	18–60 years [43 years]	5 male/8 female	Varied	> 4 years	Excluded (MNI coordinates not available)
	Lutz et al.	2008	16/16	29–64 years	14 male/2 female	Buddhist	(45 years)	Included
	Khushu et al.	2005	11/0	32–65	10 male/1 female	Brahmakumari Rajayoga	> 3 years	Excluded (MNI coordinates not available)
	Ritskes et al.	2003	11/0	32–62	8 male/3 female	Zen	15–25 years (8 years)	Excluded (MNI coordinates not available)

**Fig. 2** Mango images of ALE activation clusters (Table 2): brain activation during meditation – axial view

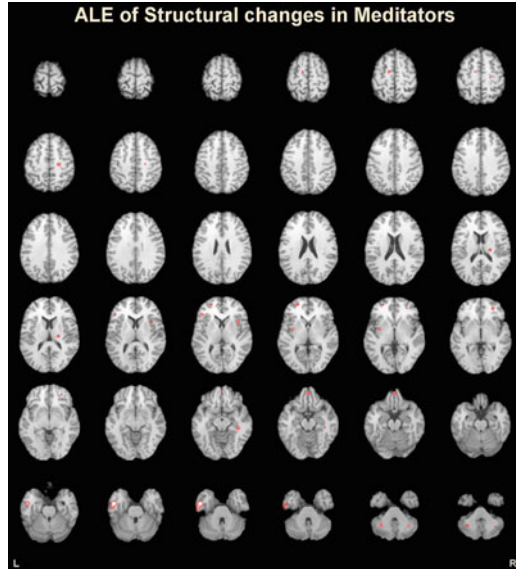


**Fig. 3** Mango images of ALE activation clusters (Table 2): brain activation during meditation – sagittal view



Hölzel et al. (2008) used voxel-based morphometry to measure the gray matter concentration in meditators versus non-meditators. Gray matter concentration (GMC) was found to be greater in meditators than non-meditators in the right hippocampus and the right anterior insula. Concentration in the left inferior temporal gyrus showed a trend toward significance. The GMC of the medial orbitofrontal

**Fig. 4** Mango images of ALE volume clusters (Table 3): differences in brain structure between meditators and controls – axial view



cortex was positively correlated with hours of practice. There was a positive correlation between total hours of training in meditation and mean GMC within the left inferior temporal gyrus. This suggests a causal relationship (Holzel et al. 2008).

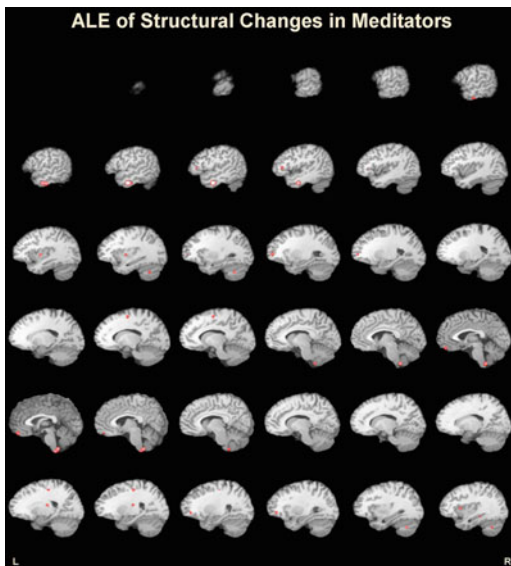
Vestergaard-Poulsen et al. (2009) found greater gray matter density in meditators versus controls in the medulla oblongata, left superior frontal gyrus, left inferior frontal gyrus, anterior cerebellum, and the left fusiform gyrus. Structural differences were also seen in the dorsal medulla gray matter/dorsal motor nucleus of the vagal nerve (regions of autonomic respiratory control and vagal tone). There was no correlation between structure and hours of practice (Vestergaard-Poulsen et al. 2009).

Luders et al. (2009) reported that there were significantly greater gray matter volumes in meditators versus controls in the right orbitofrontal cortex, thalamus, posterior superior parietal lobule, and inferior temporal gyrus as well as the right and left paracentral lobule. Significantly larger hippocampal volumes were also seen. Global cerebral measurements were the same for meditators and controls. Type of meditation practiced had no impact on results. Number of years practiced did not correlate with GM volume (Luders et al. 2009).

In summary, among studies measuring differences in brain structure between meditators and controls, differences are noted most frequently in the frontal and temporal cortices as well as subcortical regions including the hippocampus, thalamus, brainstem, and cerebellum.

ALE meta-analysis of studies measuring the difference between meditators and non-meditators revealed the greatest cluster to be in the left inferior temporal gyrus. The second greatest cluster was found in the brainstem (noted visually) but fell outside of the normalized brain used here. Multiple other areas of differential cluster size were found, but these were much smaller than the two largest clusters (see Figs. 4 and 5, Table 3). (See Appendix 2 for details of extracted coordinates.)

**Fig. 5** Mango images of ALE volume clusters (Table 3): differences in brain structure between meditators and controls – sagittal view



## Discussion

Neuroplasticity refers to the ability of the nervous system to adapt to internal and external stimuli. Magnetic resonance imaging allows assessment of meditation-associated brain activity, differential brain activation in meditators versus non-meditator controls (a training effect), and subtle *in vivo* structural differences between meditators and controls.

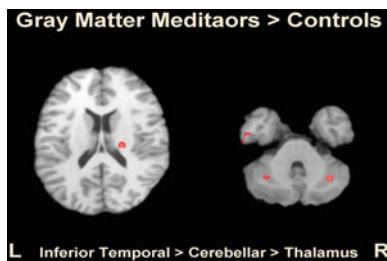
In the studies of brain activation reviewed here, fMRI demonstrates that meditation is associated with activation in a variety of areas, most consistently the frontal and parietal cortices, and the hippocampus. Meta-analysis revealed the most significant clusters of brain activation during meditation to be in the left frontal and parietal cortices. This result is consistent with the individual studies. Authors of the studies reviewed here speculate that meditation is associated with a training effect and that activation in reported areas is associated with the cognitive tasks required during meditation: attention/focus, management of discursive thoughts, and emotional regulation.

Four studies (130 subjects' total) measured structural differences in the brains of meditators and controls (Vestergaard-Poulsen et al. 2009; Holzel et al. 2008; Luders et al. 2009; Pagnoni and Cekic 2007). These studies found greater volumes of cortical, hippocampal, and subcortical gray matter in meditators as compared to controls. Specific structural differences varied between studies. Meta-analysis appeared to adequately summarize individual study findings and demonstrated the largest structural difference to be in the inferior temporal gyrus.

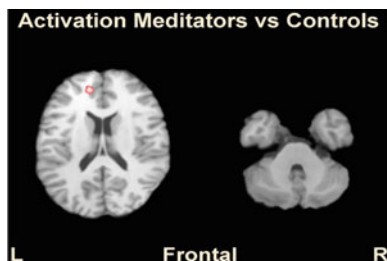
**Table 3** ALE meta-analysis: differences in brain structure between meditators and controls

Author	Year	Meditators/controls	Age range [mean]	Sex	Type of meditation	Duration of practice (mean)	Meta-analysis included/excluded (reason)
Structural differences between meditators and non-meditators							
Luders et al.	2009	22/22	30–71 years [53.9 years]	13 male/13 female	Varied (Vipassana, Zen, Samatha, others)	5–46 years (24 years)	Included
Lazar et al.	2005	20/15	[38 years]	13 male/7 female	Buddhist	9 ± 7 years	Excluded (MINI coordinates not available)
Hölzel et al.	2008	20/20	[34 years]	16 male/4 female	Vipassana	2–16 years (9 years)	Included
Vestergaard-Poulsen et al.	2009	10/10	[55 years]	6 male/4 female	Buddhist	14–31 years (16 years)	Included
Pagnoni et al.	2007	13/13	[37 years]	10 male/3 female	Buddhist	> 3 years	Included
Shimmomura et al.	2008	8/0	[41 years]	8 male/0 female	Buddhist	> 10 years	Included
Brefczynski-Lewis et al.	2007	14 expert meditators/16 novice meditators/11 incentivized novice meditators	[47 years]	Not given	Buddhist	10,000–54,000 total hours	Included
Hölzel et al.	2007	15/15	[34 years]	12 male/3 female	Vipassana	2–16 years (8 years)	Included
Lazar et al.	2000	5/0	22–45 years	4 male/1 female	Kundalini	> 4 years	Included
Short et al.	2007	13/0	18–60 years [43.5 years]	8 female	Varied	> 4 years	Excluded (MINI coordinates not available)
Lutz et al.	2008	16/16	29–64 years	14 male/2 female	Buddhist	(45 years)	Included
Khushu et al.	2005	11/0	32–65	10 male/1 female	Brahmakumari Rajayoga	> 3 years	Excluded (MINI coordinates not available)
Ritskes et al.	2003	11/0	32–62	8 male/3 female	Zen	15–25 years (8 years)	Excluded (MINI coordinates not available)

**Fig. 6** Structural differences between meditators and controls: representative volume clusters (Inferior Temporal Lobe, Cerebellum, and Thalamus)



**Fig. 7** Brain activity during meditation: representative activity cluster (*Left Frontal Region*)



In several domains, intensive training has been found to increase gray matter in regions relevant to a learned task – increased gray matter in the posterior intraparietal sulcus (known to be important perceptual-motor coordination and visual attention) in jugglers, for example. In the current analysis, regional activation during meditation (most prominent in the frontal cortex) did not predict structural differences between meditators and controls (most prominent in the inferior temporal gyrus) (see Figs. 6 and 7).

There are several potential reasons for failure of meditation-associated brain activity to predict region-specific structural differences. First, the exact relationship between neural activity and the BOLD signal has yet to be elucidated. Limits in knowledge of precisely what neuronal activity (i.e., excitation or inhibition) is reflected by the hemodynamically-dependent BOLD signal limits the degree to which inferences can be drawn from its measurement. Second, as an extension of this principle, the quantity of information processing by the brain does not always correlate with metabolic activity. Task practice can result in increased performance efficiency and simultaneous decrease in brain activity as measured by fMRI. This results in confusion as to how to interpret fMRI results. For example, in the current review Brefczynski-Lewis, et al. found that meditators with more hours of practice showed less activation than meditators with fewer hours of practice. They attribute this to a “...quieter mental state, such that tasks...become more effortless” (Brefczynski-Lewis et al. 2007). On the other hand, Short, et al. found that long-term meditators demonstrated more activity in attention-related brain structures than short-term meditators and interpreted this to reflect greater expertise in meditation (Short et al. 2007). Thus, opposite changes in brain activation have been interpreted as reflecting the same thing – greater task proficiency. Until the relationship between

brain activity and cognitive processes is better defined, interpreting the cognitive processes represented by fMRI-based brain activity will remain obscure. Third, results from fMRI studies of meditation potentially reflect experimental design more than the cognitive process of meditation itself. Specifically, the switching of attention necessary with the boxcar design used in these studies could be as responsible for activity in attention-related brain structures as meditation itself. Fourth, neuroscience has yet to fully characterize neuroplasticity at the cellular level. Some brain regions and cell types may respond to training with region specific change in volume while others do not. Fifth, it is also possible that neuroplasticity associated with meditation is not related to a region-specific training effect, but rather to a generally healthier physical environment created by another meditation related factor such as down-regulation of the hypothalamic-pituitary-adrenal (HPA) axis. The findings of Pagnoni et al., that total gray matter volume showed a negative correlation with age in controls but not in meditators, supports this notion. Finally, it is important to remember that meditation is a psychological construct. It can be difficult to operationalize and exists potentially without a definable physical locus or network of loci. Whether or not such complicated thought processes can be characterized by localized brain changes has yet to be determined.

This study includes a number of limitations. First, the total number of studies analyzed here is small. Additional data from future experiments has the potential to significantly impact these results. Second, while ALE meta-analysis is appropriate for evaluation of fMRI studies measuring brain activation and MRI based structural studies separately, there is no precedence in the literature for comparing results from different study subtypes. This practice should be considered speculative at this time. Third, meta-analysis depends on the quality and reporting of constituent studies. Studies evaluated here were inconsistent in reporting potentially important covariates such as general health, and medication use.

The notion that meditation could train the brain in such positive mental attributes as attentiveness, self-regulation, and emotional discrimination and that these attributes could be instantiated structurally has profound implications that warrant further exploration. The study of meditation-associated neuroplasticity would be moved forward most expediently by performing a randomized controlled trial of participants before and after introduction of a meditation program. Recent data indicating shorter usage dependent time-scales for structural change makes such studies more feasible than previously recognized. Simultaneous collection of neurophysiological data including measures of attention and emotional regulation would help to corroborate or refute conclusions drawn from neuroimaging studies, and avoid the need (and trap) of reverse inference. While the authors of the studies reviewed here focus on the cognitive process of attention and emotional regulation during meditation, surprisingly little attention is paid to brain activity related to the hypothalamic-pituitary-adrenal (HPA) axis and relaxation during meditation. Building on the neurophysiological model of the HPA axis proposed by (Newberg et al. 2003) would help to identify relevant brain structures and allow correlation of neuroimaging and hormonal test results (Newberg and Iverson 2003). Improved modeling would also help to determine whether possible meditation-mediated neuroplasticity is related to a general improvement in health or to activation-specific stimuli.

In conclusion, training in some domains leads to measurable structural plasticity in the brain. Previous authors have suggested that meditation is a form of mental training which is associated with region specific structural changes. While it was theorized that studies measuring brain activation during meditation would predict region-specific neuroplasticity, findings here refute this hypothesis. This may have more to do with methodology than the refutability of the hypothesis itself. The notion that mental practices can enhance neuroplasticity warrants further investigation. Such exploration promises to suggest new ways of training the brain and promoting its longevity. And, it may resurrect some old methods along the way.

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## Appendix 1 Extracted Coordinates: Brain Activation During Meditation

Author	Year	Hemisphere	Anatomic Region	x	y	z	Z max t	p value
Shimomura et al.	2008	Left	Superior frontal gyrus	0	5	62	4.71	<0.05
		Left	Superior frontal gyrus	-8	1	63	3.89	<0.05
		Left	Superior frontal gyrus	-4	-8	67	3.41	<0.05
		Left	Superior frontal gyrus	-2	6	51	4.14	<0.05
		Left	Medial frontal gyrus	-2	14	49	4.56	<0.05
		Left	Medial frontal gyrus	0	27	41	3.82	<0.05
		Left	Middle frontal gyrus	-44	14	42	5.2	<0.05
		Left	Middle frontal gyrus	-55	19	29	4.05	<0.05
		Left	Middle frontal gyrus	-50	6	44	3.49	<0.05
		Right	Supramarginal gyrus	51	-53	36	4.95	<0.05
		Right	Supramarginal gyrus	61	-43	33	4.12	<0.05
		Right	Angular gyrus	44	-61	33	4.14	<0.05
		Right	Medial frontal gyrus	2	14	47	4.59	<0.05
		Left	Inferior frontal gyrus	-32	35	7	4.11	<0.05
		Left	Inferior frontal gyrus	-44	43	-2	3.59	<0.05
		Left	Inferior frontal gyrus	-35	24	6	3.58	<0.05
		Left	Middle frontal gyrus	-40	12	51	3.82	<0.05
		Left	Middle frontal gyrus	-32	12	55	3.72	<0.05
Left	Middle frontal gyrus	-28	5	55	3.61	<0.05		

(continued)



(continued)

Author	Year	Hemisphere	Anatomic Region	x	y	z	Z max t	p value		
Brefczynski-Lewis et al.	2007	Left	Middle frontal gyrus/ Inferior frontal gyrus	-49	29	19	3.2	<0.005		
		Right	Superior frontal gyrus	31	42	31	2.4	<0.05		
		Left	Middle frontal gyrus/ dorsal lateral prefrontal cortex	-21	6	50	2.5	<0.05		
		Left	Rectal gyrus	-0.5	43	-26	3.4	<0.005		
		Left	Precentral, dorsal lateral prefrontal cortex	-34	-2	36	3	<0.01		
		Left	Intraparietal sulcus, superior parietal, supramarginal gyrus	-24	-61	46	3.2	<0.005		
		Right	Superior parietal	14	-62	54	3.8	<0.005		
		Right	Cuneus	22	-85	11	4	<0.005		
		Left	Middle temporal gyrus, inferior frontal gyrus	-38	-7	-26	5.1	<0.005		
		Right	Middle temporal gyrus	54	-12	-8	3.2	<0.005		
			Fusiform	-42	-55	-16	3.5	<0.005		
		Left	Putamen	-30	-20	3	2.8	<0.01		
		Right	Lentiform, parahippocampus	29	-42	11	2.9	<0.01		
			Cerebellum, declive, culmen	-4	-56	-14	3.3	<0.005		
		Left	Cerebellar tonsil	-22	-39	-40	3.3	<0.005		
		Left	Anterior middle frontal gyrus	-26	43	7	-3.17	<0.01		
		Hölzel et al.	2007	Left	Anterior cingulate cortex	-12	42	12	5.11	0.002
				Right	Anterior cingulate cortex	9	48	9	3.97	0.025
Left	Dorsal medial prefrontal cortex			-12	45	15	4.48	0.017		
Left	Dorsal medial prefrontal cortex			0	48	39	4.2	0.031		
Right	Dorsal medial prefrontal cortex			6	51	3	4.36	0.017		
Right	Dorsal medial prefrontal cortex			3	48	39	4.1	0.029		
Left	Inferior temporal			-51	-3	-42	13.43	0.000		
Left	Inferior orbital frontal			-45	36	-21	8.26	0.000		
Right	Cerebellum			36	-84	-42	7.98	0.000		
Right	Rectus			15	21	-21	7.92	0.000		
Left	Cerebellum			-24	-93	-36	7.73	0.000		
Left	Superior medial frontal			-9	63	6	7.45	0.000		

(continued)

(continued)

Author	Year	Hemisphere	Anatomic Region	x	y	z	Z max t	p value
Lazar et al.	2000		Anterior cingulum	6	33	0		<0.001
			Basal ganglia (putamen)	28	-15	-6		<0.001
			Midbrain	-15	-15	-15		<0.001
			Midbrain	0	-12	-9		<0.001
			Parahippocampal gyrus	-25	-24	-15		<0.001
			Superior frontal gyrus	-6	24	50		<0.001
			Middle frontal gyrus	-40	30	37		<0.001
			Medial frontal gyrus	12	48	9		<0.001
			Parietal lobule	-21	-48	53		<0.001
			Superior parietal lobule	-21	-63	53		<0.001
			Superior parietal lobule	-31	-57	53		<0.001
			Superior parietal lobule	-28	-54	43		<0.001
			Superior/inferior parietal lobule	40	-60	46		<0.001
			Inferior parietal lobule	-34	-36	43		<0.001
			Superior temporal gyrus	59	-60	28		<0.001
			Middle temporal gyrus	59	-57	3		<0.001
			Parahippocampal gyrus	-28	-21	-12		<0.001
			Precentral gyrus	46	-12	53		<0.001
			Postcentral gyrus	-25	-39	62		<0.001
			Paracentral lobule	-6	-33	65		<0.001
Lutz et al.	2008	L/R	Precuneus	-5	-55	52	5.8	<0.0005
		Right	Supramarginal gyrus	52	-43	37	6.8	<0.0005
		L/R	Inferior parietal lobule	46	-40	47	6.1	<0.0005
		L/R	Anterior insula	37	15	1	4.8	<0.0005
		L/R	Superior temporal sulcus	54	-38	14	5.7	<0.0005
		L/R	Superior temporal gyrus	54	5	-7	5.2	<0.0005
		Right	Superior parietal lobule	34	-60	46	6.1	<0.0005
		L/R	Posterior cingulate gyrus	6	-40	40	5.5	<0.0005
		Right	Middle temporal gyrus	58	-47	-3	6.4	<0.0005
		L/R	Parahippocampus	12	-39	4	5.3	<0.0005
		L/R	Fusiform gyrus	48	-38	-17	4.93	<0.0005
		L/R	Cerebellum	16	-48	-12	6.1	<0.0005
		Right	Anterior cingulate gyrus	5	24	37	4.1	<0.005
		Right	Medial frontal gyrus	9	6	42	4.1	<0.005
		Right	Mid frontal gyrus	22	9	58	3.4	<0.005
L/R	Brainstem	3	-22	-6				

## Appendix 2 Extracted Coordinates: Meta-Analysis of Differences in Brain Volume Between Meditators and Controls

Author	Year	Study measure	Hemisphere	Anatomic region	x	y	z	Z max	t	p value
Luders et al.	2009	GM volume	Right	Orbito-frontal cortex	28	41	-3			0.0001
			Left	Inferior temporal lobe	-45	-8	-28			0.0003
			Right	Thalamus	21	-22	14			0.0003
			Left	Paracentral lobe	-12	-9	54			0.0004
			Right	Paracentral lobe	22	-23	48			0.0005
Hölzel et al.	2008	GM concentration	Right	Hippocampus	38	-32	-12			0.027
			Right	Anterior insula	36	12	6			0.022
			Left	Inferior temporal gyrus	-49	-9	-28			0.058
			Medial	Orbitofrontal cortex	1	45	-16			0.023
			Right	Medulla oblongata	3	-37	-58	5.24		<0.05
Vestergaard-Poulsen et al.	2009	GM density	Left	Superior frontal gyrus	-24	50	4	4.29		<0.05
			Left	Inferior frontal gyrus	-44	28	6	3.96		<0.05
			Bilateral	Cerebellum	33	-59	-36	4.14		<0.05
			Right	Medulla Oblongata	5	-45	-51	4.89		<0.05
			Left	Medulla Oblongata	5	-46	-51	5.49		<0.05
			Left	Fusiform gyrus	-52	-19	-29	4.75		<0.05
			Left	Cerebellum	-29	-58	-37	4.14		<0.05
Pagnoni et al.	2007	GM volume	Left	Putamen	-33	-5	2	5.45	0.001	

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