

# Brain Structure and Meditation

## How Spiritual Practice Shapes the Brain

Ulrich Ott (1), Britta K. Hölzel (1, 2) & Dieter Vaitl (1)

1 Bender Institute of Neuroimaging, University of Giessen, Germany

2 Massachusetts General Hospital, Harvard Medical School, Boston, MA, U.S.A.

**Abstract** Meditation practices can be conceived as specific types of mental training with measurable effects on the function and structure of the human brain. This contribution narratively reviews recent morphometric studies that compared experienced meditators with matched controls. While meditation types and measures differed between studies, results were remarkably consistent. Differences in gray matter (GM) volume and density were found in circumscribed brain regions which are involved in interoception and in the regulation of arousal and emotions, namely insula, hippocampus, prefrontal cortex, and brainstem. The normal age-related decline in GM volume and in attentional performance was present in controls but not in meditators. These findings need to be replicated in longitudinal studies in order to confirm the causal role of meditation training. Future research has to elucidate effects of these structural changes on neural activity and mental functioning during behavioral tasks.

### Introduction

For many centuries, meditation has been practiced by mystical branches of major religions for promoting spiritual development, for gaining insight into reality, and for attaining transcendental states of consciousness. From a scientific perspective, the effects of these traditional exercises are based on the plasticity of the brain. Sustained efforts to focus attention and to cultivate emotional balance leave traces in the underlying neural substrate and circuitry. Over time, these changes in brain structure in turn support the intended changes in mental faculties and personality.

The current contribution reviews findings of structural differences in the brains of advanced meditation practitioners when compared to non-meditating controls. Increases in GM density and cortical thickness of specific brain regions may pro-

vide objective indicators for the enhancement of particular self-regulation skills. Meditation techniques involve the training and development of certain mental abilities or qualities, e.g. awareness of bodily sensations, focusing of attention, emotion regulation etc. Often such heightened skills and improved cognitive abilities are referred to as “expansion of consciousness”. Significant improvements detectable at the cognitive-behavioral level, such as one’s ability to control attention, regulate emotion, and bring awareness to bodily sensations, should also be mirrored in morphological changes at the neural level. The popular idea of “consciousness expansion through meditation” can thus be understood more scientifically by understanding how the underlying neural structures are modified by meditation practices.

## **Morphological differences in meditation practitioners**

Up to now, five studies on structural differences between meditation practitioners and controls have been conducted and will be reviewed here (for a summary of findings, see Figure 1 and Table 1 and 2).

The first study by Lazar et al. (2005) compared cortical thickness of 20 Buddhist insight meditation practitioners and 15 matched controls. Insight meditation practice aims at cultivating a nonjudgmental awareness of the internal and external stimuli present in each moment (“mindfulness”). On average, participants meditated for 9.1 years (SD = 7.1 years), practicing about 40 minutes per day.

Statistical analyses revealed differences in cortical thickness between groups in the right anterior insula and the right middle and superior frontal sulci. The cortex of meditation practitioners was significantly thicker in both regions. In the prefrontal cortex, the effect was most likely caused by an age-related decrease of cortical thickness in the control group which was absent in the meditation group. The authors argue that the strong effect in the right anterior insula could be due to the extensive training in breath awareness and in maintaining attention to visceral sensations.

Slowing of the breathing rate between a baseline condition and the first six minutes of meditation showed a strong correlation with the amount of practice and was taken as a physiological indicator of meditation experience. Within the meditation group this measure was correlated with cortical thickness in a region in the inferior occipito-temporal visual cortex and, when controlling for age, also with cortical thickness in the right anterior insula. The latter finding was taken as further evidence that training in interoceptive awareness during meditation could be responsible for increased cortical thickness in the right anterior insula, since this structure is involved in the meta-representation of the body scheme, homeostasis, and associated visceral sensations.

Effects of meditation on GM volume and on cognitive performance were investigated in a subsequent study by Pagnoni and Cekic (2007). Here, 13 Zen medita-

tors with more than three years of daily practice were compared to a same-size group of matched controls. Zen meditation was characterized as a state of openness towards the flow of mental events while maintaining a straight sitting posture and a natural breathing pattern. Analyses were performed with the voxel-based morphometry (VBM) toolbox (<http://dbm.neuro.uni-jena.de/vbm>) running under SPM5 (<http://fil.ion.ucl.ac.uk/spm/software/spm5>).

In controls, total GM volume was negatively correlated with age ( $r = -.54$ ,  $p = .056$ ) whereas in the meditation group virtually no correlation was present ( $r = .006$ ,  $p = .83$ ). The Age  $\times$  Group interaction for total GM volume failed to reach significance (ANCOVA:  $t(19) = 1.82$ ,  $p = 0.08$ ). However, a significant cluster for this interaction was found in the left putamen (combined threshold of  $p = 0.001$ , uncorrected, and cluster size  $k > 1000$  voxels), where GM volume even showed a trend to increase with age in the meditation group (controls:  $r = -.80$ ,  $p = .0011$ ; meditators:  $r = .55$ ,  $p = .063$ ).

The authors also assessed cognitive performance of participants with a computerized attention task, which required monitoring of a series of digits and responding to target stimuli by pressing a button as fast as possible. Accuracy of responses and reaction times were used as performance measures.

Target sensitivity and speed of responses decreased significantly with age in the control group but not in the meditation group. According to the authors, this effect could be directly related to the differences in the left putamen, a region involved not only in motor control but also in attention processing and cognitive flexibility. Conscious regulation of attention and control of the body posture during meditation training could possibly counteract an age-related decline in this region and explain why elderly Zen practitioners retained a high level of cognitive performance.

Hölzel et al. (2008) studied 20 advanced practitioners of Vipassana meditation in the tradition of S. N. Goenka and 20 controls, matched for sex, age, education, and handedness. This meditation training is focused on awareness of breathing and attending to bodily sensations (“body scan”). On average, meditators had practiced 8.6 years (SD = 5.0 years) daily for one hour in the morning and one hour in the evening. Analysis of structural images was done with the VBM toolbox under SPM2. Results were reported for differences in GM concentration, i.e. the statistical probability that a voxel contains GM.

Meditators had a significantly higher concentration of GM in three regions: left inferior temporal gyrus, right anterior insula, and right hippocampus. The left inferior temporal gyrus was also found to be activated during meditation in a functional study with the same participants (Hölzel et al., 2007). Moreover, GM concentration in this region was correlated with the amount of meditation practice. Increased GM concentration in the right anterior insula replicated the finding by Lazar et al. (2005) and was presumably likewise related to the strong focus on interoceptive awareness in this meditation tradition. The third finding of increased GM concentration in the right hippocampus was attributed to training in arousal regulation. High levels of stress are known to impair neuronal growth in this brain

region. As part of the limbic system, the hippocampus plays an important role in the appraisal of situations and emotional reactivity. The increase in GM in this region could reflect an enhanced ability to reduce autonomic arousal level and to maintain a state of inner peace and serenity in stressful circumstances.

Furthermore, GM concentration in the orbitofrontal cortex was positively correlated with meditation practice (whole-brain regression analysis for the meditation group, where the amount of practice was entered as a regressor). This region has been associated with the modification of responses to aversive stimuli, which is an integral part of emotion regulation training during meditation, namely the maintenance of equanimity when confronted with painful sensations.

A Danish research group (Vestergaard-Poulsen et al., 2009) investigated ten practitioners of Tibetan meditation involving attention of breathing, the cultivation of positive attitudes (loving-kindness, compassion), and a state of open awareness towards any content appearing in the mind. The experienced meditators (practice:  $M = 16.5$  years;  $SD = 5.1$  years; 2.2 hours per day) were compared to an age-matched control group of equal size. High-resolution structural scans were analyzed with the VBM toolbox under SPM5.

A significant higher concentration of GM in meditators was found in circumscribed parts of the medulla oblongata, namely the solitary tract nucleus. This region of the brain stem is involved in the control of respiration and the vagal modulation of cardiac function. Increased GM concentration was also found in the prefrontal cortex (left superior and inferior frontal gyrus) and in the anterior lobe of the cerebellum. No correlation with the amount of practice was found. The authors argue that a ceiling effect in their group of highly experienced meditators could be responsible for the absence of the correlation.

The most recent study by Luders et al. (2009) compared 22 long-term practitioners ( $M: 24.2$  years,  $SD = 12.4$  years) of different traditions (Zen, Samatha, Vipassana and “others”) with 22 control datasets matched for gender and age, taken from a database of normal adults. Data processing was performed with SPM5 and the VBM toolbox. Global analysis of GM volume was supplemented by a region-of-interest analysis based on a review of the findings of Lazar et al. (2005) and Hölzel et al. (2008). Therefore, regions-of-interest included the left inferior temporal gyrus, the right insula, the right hippocampus, and the right superior and middle frontal gyri.

Results were consistent with the findings by Hölzel et al. (2008). Meditators showed significantly more GM volume in the left inferior temporal gyrus, the right hippocampus, and the right orbito-frontal gyrus. In addition, meditators had more GM volume in the right thalamus. However, no differences in the right insula were detected and no correlation was found with the duration of practice. The authors suggest that morphological changes are likely to occur primarily within the first years of practice. Their sample contained only longstanding practitioners (at least 5 years, mostly above 10 years); hence a significant correlation could not be expected. The authors explain the lack of differences in the right insula with the heterogeneity of practices of the meditators in their study. The finding of higher

GM volume in the thalamus was related to its function to gate sensory information and to focus attention.

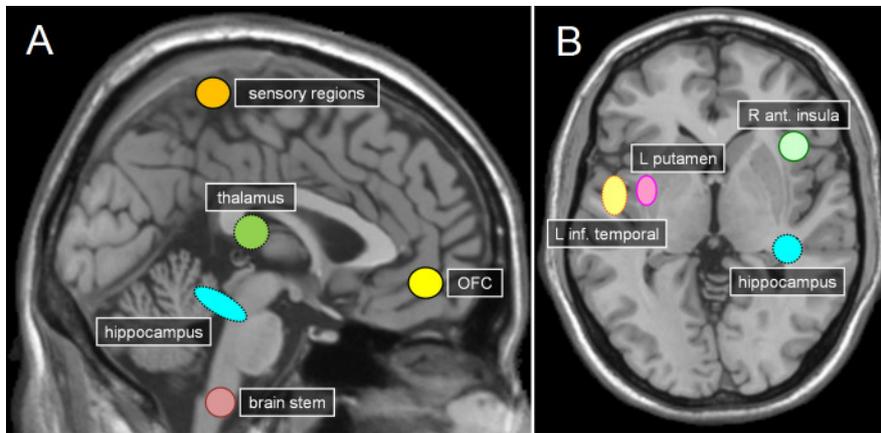
**Table 1: Overview of morphometric studies on meditation.**

Authors, year	Meditation type (practice)	N Med / Con*	Measures	Main results
Lazar et al., 2005	Insight meditation (9.1 years)	20 / 15	Cortical thickness	Med > Con: right anterior insula & prefrontal cortex Med: no decrease with age
Pagnoni & Cekic, 2007	Zen (> 3 years)	13 / 13	GM* volume, attention task	Med: no age-related decline in left putamen; no decrease in response speed and accuracy
Hölzel et al., 2008	Vipassana (8.6 years)	20 / 20	GM concentration	Med > Con: left inferior temporal gyrus, right anterior insula, right hippocampus
Vestergaard-Poulsen et al., 2009	Tibetan Buddhist Meditation (16.5 years)	10 / 10	GM concentration & volume	Med > Con: solitary tract nucleus, left prefrontal cortex, cerebellum
Luders et al., 2009	Zazen, Vipassana, Samatha & others (24.2 years)	22 / 22	GM volume	Med > Con: right orbito-frontal cortex, right thalamus, left inferior temporal gyrus, right hippocampus

\* Note: Med = Meditators, Con = Controls; GM = gray matter

**Table 2: Summary of findings and interpretations.**

Structure	Studies	Meditation training	Mental faculties
Right anterior insula	Lazar et al., 2005 Hölzel et al., 2008	Awareness of breathing sensations, body scan	Interoception, awareness of bodily feelings
Orbito-frontal cortex	Hölzel et al., 2008 Luders et al., 2009	Equanimity, inhibition of automatic responding	Emotion regulation, modifying reactions to aversive stimuli
Right hippocampus	Hölzel et al., 2008 Luders et al., 2009	Bodily relaxation while staying vigilant, distanced observing of thoughts and emotions	Regulation of arousal
Left inferior temporal gyrus	Hölzel et al., 2008 Luders et al., 2009	Awareness of present moment, state of being	Mindful state, pleasure, connectedness
Right thalamus	Luders et al., 2009	Attend to a chosen meditation object	Focusing of attention
Left putamen	Pagnoni & Cekic, 2007	Awareness of present moment, keeping static body position	Sustained attention
Brain stem, solitary tract nucleus	Vestergaard-Poulsen et al., 2009	Observing a deep and regular breathing pattern	Respiratory and cardiovascular control



**Fig. 1: Regions, in which differences between meditators and non-meditators were found: Thalamus (Luders et al., 2009), right hippocampus and left inferior temporal gyrus (Hölzel et al., 2008; Luders et al., 2009), orbito-frontal cortex (OFC; Luders et al., 2009), brain stem (Vestergaard-Poulsen et al., 2009), right anterior insula (Lazar et al., 2005; Hölzel et al., 2008), and sensory cortex (Lazar et al., 2005). A: sagittal view; B: axial view. Regions that are not located in this plane are depicted with dotted lines.**

## Discussion

The reviewed findings suggest that the sustained efforts of meditation practitioners to modulate attention, arousal, and emotional responses could change the underlying neural circuitry in the thalamus, hippocampus, orbitofrontal cortex, and brainstem. Furthermore, the regular engagement in **introspection** is likely to improve the ability to discern subtle visceral sensations and to increase the awareness of the momentary bodily and emotional states. On the neural level, it has been shown that a meta-representation of bodily sensations is actually generated in the right anterior insula (Craig, 2009), which is enlarged in those meditators practicing the body scan.

However, the authors of all reviewed studies stress the need of longitudinal studies to investigate the causal role of meditation regarding the observed differences and to rule out the alternative explanation, namely self-selection. Perhaps people who decide to begin meditation have certain pre-existing differences in brain structure compared to those who don't, or perhaps those with a certain neural constitution are more likely to maintain a long-term meditation practice. In particular, the lack of an age-related decline in gray matter has to be interpreted with great caution since people with cognitive impairments are likely to discontinue meditation practice. Thus, participants of control groups have to be matched also

regarding such kinds of selection pressure, e.g., by recruiting them from a population of chess players participating regularly in tournaments. In a similar way, longitudinal studies will have to employ active control groups. Meditation training needs to be compared with other sorts of mental training to identify specific effects of the respective meditation technique. The following are a few of the key questions that have to be addressed by future studies within this emerging field of contemplative neuroscience:

1. Future research should compare different meditation traditions and techniques, in order to differentiate between common and specific effects. For example, studies should directly compare meditations with different kinds of attention regulation (guided vs. volitional; cf. Newberg & Iversen, 2003), different ways of focusing attention (focused meditation vs. open awareness), and different intentional goals (e.g., cultivating compassion vs. attention training vs. relaxation) – all of which will likely rely on different neural mechanisms and produce different neural and behavioral effects.
2. In order to grant a better understanding of the relevance of morphological changes, it will be indispensable to investigate how structural changes are related to brain function and behavior. For example, are morphological differences associated with functional brain activation patterns (detectable by functional magnetic resonance imaging and electroencephalography) during the performance of relevant tasks? Is the interplay between different brain regions (functional connectivity) impacted by meditation practice? And most importantly, are morphological differences reflected in subjective measures of well-being and objective measures of behavior and performance?
3. Future studies should also investigate how neural connections between brain regions change as a result of practice. New imaging modalities, (e.g. fractional anisotropy in diffusion tensor imaging) have to be applied in order to apply quantifiable analyses to such complex processes.
4. Future research should also track the changes in morphological measures across short periods of time, in order to figure out the time frame within which such modifications occur. Gray matter changes detectable in anatomical magnetic resonance imaging have been reported after a period of as few as seven days (Driemeyer et al., 2008). Also, the amount of training should be actively manipulated, to detect how much training is required to obtain a measurable effect.

### *A Glimpse into the Future*

Studies addressing these questions are constantly emerging. In other domains, it has been shown that differences in regional gray matter are directly related to

functional abilities (Gaser & Schlaug, 2003; Ilg et al., 2008; Maguire et al., 2000; Mechelli et al., 2004; Milad et al., 2005).

In the field of meditation research, a recently published study investigates the relationship between pain sensitivity and cortical thickness in Zen meditators, linking morphological findings in meditation to changes in behavioral measures (Grant et al., 2008). Zen meditators showed lower thermal pain sensitivity (defined as the temperature required for producing a subjective experience of moderate pain) compared to non-meditators (Grant & Rainville, 2009). When these findings on pain sensitivity measures were related to regional cortical thickness, Zen meditators showed greater cortical thickness in the right mid-anterior cingulate cortex and secondary somatosensory cortex bilaterally when compared to non-meditating control subjects (Grant et al., 2008). These brain regions are known to be involved in pain processing. A correlation analysis confirmed that individual pain sensitivity was associated with cortical thickness across the two subsamples. Pain sensitivity was reduced in participants with greater cortical thickness.

This study illustrates how relationships between morphological findings and behavioral measures should be tested in order to shed light on the neural mechanisms underlying abilities attributed to meditation training. However, it has to be kept in mind that cross-sectional studies do not allow the causal attribution of differences to the meditation training. In the above study, it is possible that both individual motivation to engage in (and maintain) meditation practice and a person's specific pain sensitivity might have a common neural basis. In order to rule out such an alternative explanation, longitudinal studies are indispensable.

The first longitudinal study to test the effect of mindfulness meditation training on brain structure has recently been presented by Hölzel et al. (under review; cf. Lazar et al., 2009). Sixteen participants underwent an 8-week Mindfulness-Based Stress Reduction (MBSR; Kabat-Zinn, 1990) course. MBSR is a group program that aims at the cultivation of mindfulness by employing different meditation practices, such as the body scan, yoga, awareness of breathing, and open awareness meditation. Anatomical magnetic resonance images were acquired before and after the training and analyzed for changes in gray matter concentration. Changes were hypothesized in those structures previously identified in the study by Hölzel et al. (2008), namely the hippocampus, right anterior insula and left inferior temporal lobe. These regions had been identified to show differences between meditators and non-meditators in at least two out of the five published studies reviewed above (see Table 2).

Data analysis confirmed longitudinal increases in regions of interest for the left hippocampus and left inferior temporal lobe. Changes in the right anterior insula could not be confirmed. Additionally, exploratory whole-brain analyses identified significant increases in gray matter concentration in other parts of the brain that are involved in introspective processes, as well as emotion and arousal regulation. This is the first longitudinal evidence that supports some of the cross-sectional differences found in earlier studies. However, the generalizability of the study by Hölzel et al. (under review) is limited, as the sample size was very small and no

control group was included. Particularly, MBSR is a complex group program, and its positive effects are likely in part attributable to meditation-unspecific effects, such as social interactions in the group. Future studies should control for such effects, e.g., by including active control conditions, such as the Health-enhancement program (HEP; MacCoon et al., 2009), which was specifically designed to control for non-specific intervention effects associated with MBSR.

In a further analysis, Hölzel et al. (2009) investigated the morphological correlate of longitudinal changes in perceived stress following MBSR. Changes in scores on the perceived stress scale (PSS; Cohen & Williamson, 1988) from before and after the eight week program were significantly correlated with changes in gray matter concentration in the right basolateral amygdala. The more participants' subjective stress scores were reduced, the more decrease in gray matter concentration was found within this region. The data illuminate a change in neural architecture underlying modifications in one aspect of subjective well-being that resulted from mindfulness meditation training.

## Summary

Morphometric studies have found differences between meditation practitioners and controls in a number of brain regions. While the assumption is plausible that these differences result from meditation practice, longitudinal studies are required to elucidate causal connections between the practice of different meditation techniques and structural changes in circumscribed brain structures.

Clearly, morphometric analyses have to be supplemented with functional and behavioral data acquired during relevant tasks. The recent studies exemplify approaches that are able to reveal the mechanisms that facilitate the benefits ascribed to meditation practice. In addition to shedding light on the mechanisms underlying the cultivation of beneficial qualities in meditators, the findings of contemplative research have the potential to inform larger inquiries into the basic mechanisms of the human nervous system, such as attentional and emotional self-regulation.

## References

- Cohen, S., & Williamson, G. M. (1988). Perceived stress in a probability sample of the United States. In S. Spacapan & S. Oskamp (Eds.), *The social psychology of health* (pp. 31–67). Newbury Park, CA: Sage.
- Craig, A. D. (2009). How do you feel — now? The anterior insula and human awareness. *Nature Reviews Neuroscience*, 10, 59–70.
- Driemeyer, J., Boyke, J., Gaser, C., Buchel, C., & May, A. (2008). Changes in gray matter induced by learning — revisited. *PLoS ONE*, 3(7), e2669.

- Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *Journal of Neuroscience*, 23(27), 9240–9245.
- Grant, J., Duerden, E., Duncan, G., & Rainville, P. (2008). *Cortical thickness and pain sensitivity in advanced Zen meditators*. Poster presented at the 12<sup>th</sup> World Congress on Pain, August 17–22, Glasgow, Scotland, UK.
- Grant, J. A., & Rainville, P. (2009). Pain sensitivity and analgesic effects of mindful states in Zen meditators: A cross-sectional study. *Psychosomatic Medicine*, 71, 106–114.
- Hölzel, B. K., Ott, U., Hempel, H., Hackl, A., Wolf, K., Stark, R., & Vaitl, D. (2007). Differential engagement of anterior cingulate and adjacent medial frontal cortex in adept meditators and non-meditators. *Neuroscience Letters*, 421, 16–21.
- Hölzel, B. K., Ott, U., Gard, T., Hempel, H., Weygandt, M., Morgen, K., & Vaitl, D. (2008). Investigation of mindfulness meditation practitioners with voxel-based morphometry. *Social Cognitive and Affective Neuroscience*, 3, 55–61.
- Hölzel, B.K., Carmody, J., Congleton, C., McCallister, A., Yerramsetti, S.M., Lazar, S.W. (under review). Meditation practice leads to increases in regional brain gray matter concentration.
- Hölzel, B. K., Carmody, J., Evans, K. C., Hoge, E. A., Dusek, J. A., Morgan, L., Pitman, R. K., Lazar, S. W. (2009). Stress reduction correlates with structural changes in the amygdale. *Social Cognitive and Affective Neuroscience* (Advance Access published September 23, 2009).
- Ilg, R., Wohlschläger, A. M., Gaser, C., Liebau, Y., Dauner, R., Woller, A., et al. (2008). Gray matter increase induced by practice correlates with task-specific activation: a combined functional and morphometric magnetic resonance imaging study. *Journal of Neuroscience*, 28(16), 4210–4215.
- Kabat-Zinn, J. (1990). *Full Catastrophe Living*. New York: Delta Publishing.
- Lazar, S. W., Kerr, C. E., Wasserman, R. H., Gray, J. R., Greve, D. N., Treadway, M. T., et al. (2005). Meditation experience is associated with increased cortical thickness. *NeuroReport*, 16, 1893–1897.
- Lazar, S. W., Hölzel, B. K., & Evans, K. C. (2009). *Neurobiological underpinnings of mindfulness and meditation*. Paper presented at the 7<sup>th</sup> Annual International Scientific Conference of the Center for Mindfulness in Medicine, Health Care, and Society. March 18–22<sup>nd</sup>, 2009.
- Luders, E., Toga, A. W., Lepore, N., & Gaser, C. (2009). The underlying anatomical correlates of long-term meditation: Larger hippocampal and frontal volumes of gray matter. *NeuroImage*, 45, 672–678.
- MacCoon, D. G., Sullivan, J. C., Davidson, R. J., Stoney, C. M., Christmas, P. D., Thurlow, J. P., & Lutz, A. (2009, 1/9/2009). *Health-enhancement program (HEP) guidelines*. Permanent URL: <http://digital.library.wisc.edu/1793/28198>.
- Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences U.S.A.*, 97(8), 4398–4403.
- Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., et al. (2004). Structural plasticity in the bilingual brain. Proficiency in a second language and age at acquisition affect grey-matter density. *Nature*, 431, 757.
- Milad, M. R., Quinn, B. T., Pitman, R. K., Orr, S. P., Fischl, B., & Rauch, S. L. (2005). Thickness of ventromedial prefrontal cortex in humans is correlated with extinction memory. *Proceedings of the National Academy of Sciences U.S.A.*, 102(30), 10706–10711.
- Newberg, A. B., & Iversen, J. (2003). The neural basis of the complex mental task of meditation: neurotransmitter and neurochemical considerations. *Medical Hypotheses*, 61(2), 282–291.
- Pagnoni, G., & Cekic, M. (2007). Age effects on gray matter volume and attentional performance in Zen meditation. *Neurobiology of Aging*, 28, 1623–1627.
- Vestergaard-Poulsen, P., van Beek, M., Skewes, J., Bjarkam, C. R., Stubberup, M., Bertelsen, J., & Roepstorff, A. (2009). Long-term meditation is associated with increased gray matter density in the brain stem. *NeuroReport*, 20, 170–174.