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Mindfulness practice leads to increases in regional brain gray matter density

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ABSTRACT

Therapeutic interventions that incorporate training in mindfulness meditation have become increasingly popular, but to date little is known about neural mechanisms associated with these interventions. Mindfulness-Based Stress Reduction (MBSR), one of the most widely used mindfulness training programs, has been reported to produce positive effects on psychological well-being and to ameliorate symptoms of a number of disorders. Here, we report a controlled longitudinal study to investigate pre–post changes in brain gray matter concentration attributable to participation in an MBSR program. Anatomical magnetic resonance (MR) images from 16 healthy, meditation-naïve participants were obtained before and after they underwent the 8-week program. Changes in gray matter concentration were investigated using voxel-based morphometry, and compared with a waiting list control group of 17 individuals. Analyses in *a priori* regions of interest confirmed increases in gray matter concentration within the left hippocampus. Whole brain analyses identified increases in the posterior cingulate cortex, the temporo-parietal junction, and the cerebellum in the MBSR group compared with the controls. The results suggest that participation in MBSR is associated with changes in gray matter concentration in brain regions involved in learning and memory processes, emotion regulation, self-referential processing, and perspective taking.

1. Introduction

Mindfulness meditation has been reported to produce positive effects on psychological well-being that extend beyond the time the individual is formally meditating. Over the last three decades mindfulness meditation practices have been increasingly incorporated into psychotherapeutic programs, to take advantage of these benefits (cf. Baer, 2003; Grossman et al., 2004). A large body of research has established the efficacy of these mindfulness-based interventions in reducing symptoms of a number of disorders, including anxiety (Roemer et al., 2008), depression (Teasdale et al., 2000), substance abuse (Bowen et al., 2006), eating disorders (Tapper et al., 2009), and chronic pain (Grossman et al., 2007), as well as improving well-being and quality of life (e.g., Carmody and Baer, 2008). Mindfulness meditation involves the development of awareness of present-moment experience with a compassionate, non-judgmental stance (Kabat-Zinn, 1990). It has been suggested that this process is associated with a perceptual shift (Carmody, 2009), in which one's thoughts and feelings are recognized as events occurring in the broader field of awareness.

Neuroimaging studies have begun to explore the neural mechanisms underlying mindfulness meditation practice with techniques such as electroencephalography (EEG) (Davidson et al., 2003; Slagter et al., 2007) and functional magnetic resonance imaging (MRI) (Farb et al., 2007; Lutz et al., 2008; Farb et al., 2010; Goldin and Gross, 2010). Recently, several cross-sectional anatomical MRI studies have demonstrated that experienced meditators exhibit a different gray matter morphometry in multiple brain regions when compared with non-meditating individuals (Lazar et al., 2005; Pagnoni and Cekic, 2007; Hölzel et al., 2008; Luders et al., 2009; Vestergaard-Poulsen et al., 2009; Grant et al., 2010). While most of the brain regions identified have been reported in only one of these studies, the divergent results are likely due to differences in participant characteristics, type of meditation, and data analysis methods (see Table 1). Group differences in the hippocampus and the right anterior insula, however, have each been identified in at least two of the studies. Furthermore, activation in both regions has been reported during meditative states (hippocampus (Lazar et al., 2000; Hölzel et al., 2007); insula (Farb et al., 2007; Lutz et al., 2008)). The hippocampus is known to be critically involved in learning and memory processes (Squire, 1992), and in the modulation of emotional control (Corcoran et al., 2005; Milad et al., 2007), while the insula has been postulated to play a key role in the process of awareness (Craig, 2009) — functions which have been shown to be important in the process and outcomes of mindfulness training (Bishop et al., 2004; Shapiro et al., 2006; Ortner et al., 2007).

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Table 1
Overview of morphometric studies on meditation.

Study	Meditation tradition	*N* meditators/ controls	Morphological measures	Regions identified greater in meditators than controls
Lazar et al. (2005)	Insight	20/15	Cortical thickness	Right anterior insula and right middle and superior frontal sulci
Pagnoni and Cekic (2007)	Zen	13/13	Gray matter volume (VBM in SPM5)	Meditators showed no age-related decline in the left putamen as compared to controls
Hölzel et al. (2008)	Insight	20/20	Gray matter density (VBM in SPM2)	Left inferior temporal lobe, right insula, and right hippocampus
Vestergaard-Poulsen et al. (2009)	Tibetan Buddhist	10/10	Gray matter density and volume (VBM in SPM5)	Medulla oblongata, left superior and inferior frontal gyri, anterior lobe of the cerebellum and left fusiform gyrus
Luders et al. (2009)	Zazen, Vipassana, Samatha and others	22/22	Gray matter volume (VBM in SPM5)	Right orbito-frontal cortex, right thalamus, left inferior temporal lobe, right hippocampus
Grant et al. (2010)	Zen	19/20	Cortical thickness	Right dorsal anterior cingulate cortex, secondary somatosensory cortex

VBM: voxel-based morphometry (Gaser), SPM: Statistical Parametric Mapping, (Wellcome Department of Cognitive Neurology, London).

A growing body of literature has demonstrated that neural systems are modifiable networks and changes in the neural structure can occur in adults as a result of training. For example, longitudinal studies have shown task-specific increases in brain gray matter as an effect of acquisition of abstract information (Draganski et al., 2006), motor skills (Draganski et al., 2004), aerobic training (Colcombe et al., 2006), and cognitive skills (Ilg et al., 2008). Cross-sectional studies have established that differences in regional gray matter are associated with performance abilities (Mechelli et al., 2004; Milad et al., 2005), suggesting that an increase in gray matter corresponds to improved functioning in the relevant area. Studies of experienced meditators have also suggested the possibility of structural plasticity, but their cross-sectional designs did not exclude the possibility of pre-existing group differences, precluding causal conclusions. Here we report a longitudinal study of gray matter changes associated with a mindfulness-based intervention. The focus of the study was to identify brain regions that changed in association with participation in an 8-week Mindfulness-Based Stress Reduction course (MBSR; Kabat-Zinn, 1990). This group program aims to improve participants' mindfulness and well-being, and reduce their levels of perceived stress. The study was an attempt to find objectively measurable neurological changes that could underlie the trait-changes associated with mindfulness practice. Changes in gray matter concentration were investigated using voxel-based morphometry. Focused analyses were conducted for the hippocampus and insula as our predefined regions of interest. Exploratory analyses were then performed on the entire brain and compared with a control group.

2. Methods

2.1. Participants

MBSR participants were recruited among individuals enrolled in four MBSR courses held at the Center for Mindfulness at the University of Massachusetts Medical School. The courses included physician- and self-referred individuals from across New England who were seeking stress reduction. Individuals were included in the study if they self-reported as physically and psychologically healthy and not taking any medications. Further inclusion criteria were as follows: no meditation classes in the past 6 months, no more than four classes in the past 5 years, or 10 classes in their lifetime; 25 to 55 years old; no contra-indications for MRI scanning (i.e., metallic implants, claustrophobia); commitment to attend all eight classes and perform the prescribed daily homework. Eighteen healthy, right-handed individuals were enrolled in the study, eight male and 10 female, with a mean age of: 37.89 years (S.D.: 4.04 years). Due to discomforts during the first MRI scanning session, two participants did not return for the second session. The resulting sample consisted of six male and 10 female participants with a mean age of 38.0 years (S.D.: 4.1 years). Ethnicities were as follows: 13 Caucasians, one Asian, one African American, and one multi-ethnic. Participants had an average of 17.7 years of education (S.D.: 1.9 years). Reimbursement for study participation was a discounted MBSR course fee.

The control sample consisted of 17 participants (11 male and six female) with a mean age of 39.0 years (S.D.: 9.2 years) and an average of 17.3 years of education (S.D.: 1.8 years). Ethnicities were as follows: 13 Caucasians, two Asians, two African American, and one Hispanic. The groups did not differ in age ($t\,(22.3) = 0.56$; $P = 0.58$), or education ($t\ (30) = -0.56$, $P = 0.58$). The study protocol was approved by the Institutional Review Boards (IRBs) of Massachusetts General Hospital and the University of Massachusetts Medical School, and written informed consent was obtained from all participants. A previous publication that investigated neural correlates of changes in perceived stress (Hölzel et al., 2009) included data from this sample.

2.2. Intervention

The MBSR program has been described extensively elsewhere (Kabat-Zinn, 1990). Briefly, it consists of eight weekly group meetings lasting 2.5 h each, plus 1 full day (6.5 h) during week 6 of the course. Formal mindfulness training exercises aim at developing the capacity for mindfulness (awareness of present-moment experiences with a compassionate, non-judgmental stance) and include a body scan, mindful yoga, and sitting meditation. During the body scan attention is sequentially guided through the entire body, observing with non-judgmental awareness the sensations in each region and ending with an awareness of the body "as a complete whole". The mindful yoga typically contains gentle stretching exercises and slow movements that are often coordinated with the breath, with emphasis placed on bringing full awareness to the moment-to-moment experience and a non-harming attitude towards the body. Participants are encouraged to investigate what feels appropriate for themselves and to honor their body's limitations. Sitting meditation practices typically begin with awareness of the sensations of breathing, then evolve to include awareness of different modalities (such as sounds, sight, taste, other body sensations, thoughts and emotions). Later, emphasis is given to open awareness meditation, where the field of awareness is expanded to include anything that appears in consciousness, or a simple awareness of one's presence in the here and now.

Participants received audio recordings containing 45-min guided mindfulness exercises (body scan, yoga, and sitting meditation) that they were instructed to practice daily at home. To facilitate the integration of mindfulness into daily life, they were also taught to practice mindfulness informally in everyday activities such as eating, walking, washing the dishes, or taking a shower. During classes, the formal mindfulness exercises were practiced, questions relating to the practice of mindfulness in everyday life were clarified and didactic instruction was given on using mindfulness for coping with stress in daily life. Historically, MBSR participants have reported a wide range