Enhanced Introspective Accuracy and Brain Grey Matter Concentration in Long-term Meditation Practitioners

by

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Abstract

The accuracy of subjective reports, especially those involving introspection of one's own internal processes, remains unclear, and research has demonstrated large individual differences in introspective accuracy. It has been hypothesized that introspective accuracy may be heightened in persons who engage in meditation practices, due to the highly introspective nature of such practices. We undertook a preliminary exploration of this hypothesis, examining introspective accuracy in a cross-section of meditation practitioners (1 - 15,000 hrs experience). Expert meditators showed significantly better introspective accuracy than novices; overall meditation experience also significantly predicted individual introspective accuracy. We then undertook a neuroimaging study (with a partially overlapping sample of meditators) to investigate possible structural brain differences between long-term meditators with high introspective accuracy, and meditation-naïve control subjects. Using magnetic resonance imaging to acquire 3D anatomical brain images, we used voxel-based morphometry to assess grey matter concentration differences between groups, and also as a function of meditation experience. Between-groups results suggest significantly greater concentrations of grey matter in primary somatosensory cortex in long-term meditators vs. controls; among meditators, grey matter concentration was found to increase in several regions key to body-awareness with increasing experience in the body-scanning meditation practice.

Preface

The methods, results and discussion of ‘Study 1: Behavioral (Introspective Accuracy)’ in this thesis are currently ‘accepted’ under the citation:

Fox K, Zakarauskas P, Dixon M, Ellamil M, Thompson E, Christoff K. (2012). Meditation Experience Predicts Introspective Accuracy. *PLoS ONE*.

KF designed the study, ran participants, analyzed data, and wrote the manuscript; PZ designed the study and ran participants; MD designed the study and ran participants; ME ran participants; ET wrote the manuscript; KC designed the study and wrote the manuscript. KF designed most aspects of the study, ran the majority of participants, analyzed all data, and wrote the great majority of the manuscript.

Data for ‘Study 2: Neuroimaging (Brain Grey Matter Concentration)’ presented here have not yet been published; ME contributed significantly to running participants and study design.

The UBC Behavioral Research Ethics Board (BREB) approved Study 1 (Behavioral) under Ethics Certificate # H10-02852. The UBC Clinical Research Ethics Board (CREB) approved Study 2 (Neuroimaging) under Ethics Certificate # H08-00153. All participants in both studies provided written informed consent.

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1 INTRODUCTION

William James exhorted us more than a century ago, “Introspective observation is what we have to rely on first and foremost and always” (James, 1890), but for much of the 20th century, psychologists did not regard introspective reports as valid data for scientific inquiry. Some contemporary researchers have doubted the very possibility of accurate introspection (Nisbett & Wilson, 1977); others have demonstrated that while introspective reports may be reliable under simple conditions, reliability decreases with increasing demands on central processing resources (Corallo, Sackur, Dehaene & Sigman, 2008).

Introspection can of course be defined in many ways; here we mean it in the straightforward manner used by James: “The word introspection need hardly be defined – it means, of course, looking into our own minds” (James, 1890). That is, in its simplest form introspection involves “considerations of our own experience… [and] our own internal states” (Jack & Roepstorff, 2002).

‘Introspective accuracy’ (IA) can putatively be quantified by a variety of methods that combine introspective reports of subjective, mental phenomena with some objective (neural, physiological, or behavioral) measure of these same phenomena. A subject’s IA with respect to a given task or process is the degree to which their introspective reports agree or correlate with such objective measures (as in Fleming, Weil, Nagy, Dolan, & Rees, 2010; and Corallo et al., 2008).

Recent research provides evidence for large inter-individual variability in introspective accuracy, which may be traceable to and predicted by differential grey matter volume in rostrolateral prefrontal cortex (RLPFC)/Brodmann Area (BA) 10 (Fleming et al., 2010). Individual differences with respect to a given skill invite the question of whether that skill can be ameliorated, and a recent study involving extensive training supports the potential for enhancing the accuracy and utility of introspective reports (Lutz et al., 2002). Further, RLPFC/BA10, thought to be a key region involved in introspection and metacognitive awareness (Christoff & Gabrieli, 2000), is amenable to voluntary up- and down-regulation through real-time functional magnetic resonance imaging (fMRI) neurofeedback training (McCaig, Dixon, Keramantian, Liu, & Christoff, 2011). This functional plasticity and structural heterogeneity (Fleming et al., 2010) in frontal regions key to introspection thus provides a plausible neural basis for inter-individual differences in introspective accuracy.

In parallel with this renewed interest in introspection, cognitive neuroscience has begun to focus on the family of mental training practices known as 'meditation' (Slagter, Davidson, & Lutz, 2011). The heavily introspective focus of many meditation practices has led to the hypothesis that experienced meditators might possess the capacity for more objective assessment of their own internal states and contents (i.e., greater introspective accuracy) (Lutz & Thompson, 2003; Lutz, Slagter, Dunne, & Davidson, 2008). Recent studies examining subjective reports alongside objective measures of autonomic arousal (heart period; Sze, Gyurak, Yuan & Levenson, 2010) and electroencephalogram (EEG) activity (Lutz, Francis, & Davidson, 2005) found that long-term meditators' introspective reports indeed correlated significantly with objective physiological measures (and were more accurate than those of controls in Sze et al., 2010), lending support to this hypothesis. The neurobiological basis for such enhanced introspective accuracy in long-term meditators remains unstudied, though a number of studies have found suggestive structural brain differences in meditators as compared with meditation-naïve controls (Table 1.2). Similarly, very little evidence yet bears on the question of whether such behavioural differences precede long-term meditation practice or result from it – i.e., whether good introspectors tend to persist in introspective practices such as meditation, or whether deliberately introspective practices such as meditation improve the accuracy and reliability of introspection.

Table 1.1: Summary of prior studies investigating introspective accuracy in meditation practitioners.

Study	**Meditation tradition**	***N* controls / meditators**	**Experience level of meditators**	**Objective Physiological Measures**	**Behavioral Results**
Lutz et al. (2005)	Tibetan Buddhist	18 / 10	15–40 yrs (10,000–50,000 hrs)	EEG	Frontal γ power significantly increased in meditators vs. controls; self-reported meditation clarity correlated with frontal γ power in meditators only
Nielsen & Kaszniak (2006)	Buddhist (no specific tradition reported)	17/11	21.2 $\pm$ 4.7 yrs	SCR; facial EMG; heartbeat detection	Self-rated emotional clarity predicted SCR in meditators but not controls; *no group differences on heartbeat detection*
Khalsa et al. (2008)	Kundalini; Tibetan Buddhist	17/K:17/TB: 13	K: 29.3 $\pm$ 6.4 yrs; TB: 24.7 $\pm$ 8.4 yrs	Heartbeat detection	No differences between meditators and controls
Sze et al. (2010)	Insight	21/Dancers: 21 / 21	7.1 $\pm$ 3.8 yrs	Heart period	Greater correlation between self-reported emotional state and heart period (meditators > dancers > controls)

EEG: electroencephalography; EMG: electromyography; K: Kundalini; SCR: skin-conductance response; TB: Tibetan Buddhist.

Here we examined *vipassana* (‘insight’) meditation (VM), which largely involves paying close attention to the inner experiences (conceptual, emotional, tactile, and visceral) associated with the current state of the body, primarily in order to better develop a non-discursive awareness centered in the present moment (Kabat-Zinn, 1994; Goenka, 2000). This form of meditation is thought to involve the meta-representation by the brain of diverse internal bodily responses and states (Lutz et al., 2008), and may, with intensive practice, lead to enhanced introspective accuracy and neural plasticity.

1.1 Study 1 (Behavioral): Introspective Accuracy

Despite the converging evidence that introspection and body-awareness may be heightened in long-term meditators of various traditions–especially VM–and despite the extensive body of objective data on tactile sensitivity in humans with which subjective reports can be compared, no study has yet examined the accuracy of introspective reports from a *cross-sectional* group of meditation practitioners. VM provides an ideal means of exploring introspective accuracy: the body-scanning meditation (BSM; *vedananupassana*) practice within this tradition focuses intensively on awareness of ambient tactile experiences of an entirely subjective nature, varying greatly in quality and intensity. Complementary scientific exploration of tactile sensibility has been extensive in humans, and has likewise shown marked variability in regional sensitivity throughout the body. Correlating subjective with objective measures of tactile sensitivity can thus provide a convenient measure of the extent to which introspective reports agree with what is to be expected from neurophysiological measures.

To explore this idea, we first gathered two sets of well-replicated, objective data on tactile sensitivity from previously published research that involved large samples of adults: (i) psychophysical discrimination and (ii) representation of body regions in primary somatosensory cortex (S1).

In his treatise *De Tactu*, Ernst Weber (1978/1834) established the now-classic two-point discrimination (2PD) task as a basic psychophysical measure, documenting the differential sensitivity of the sense of touch throughout the body; his results were replicated by Weinstein (1968). Improved neurosurgical methods later allowed direct electrophysiological exploration of S1 in humans, resulting in the famous 'sensory homunculus' illustrating the differential cortical representation of body regions (Penfield and Boldrey, 1937; Penfield and Rasmussen, 1950). The patterns of psychophysical sensitivity and cortical area are closely correlated (r = ~.70); i.e., regions of the body more sensitive by psychophysical measures tend to have a greater area of S1 dedicated to them (Weinstein, 1968) (Table 1.2).

Table 1.2: Reverse rank-ordered tactile sensitivity for each of the twenty body regions examined, according to psychophysical (2PD threshold) and cortical (area of S1, adjusted for corresponding skin surface area) measures, as reported in previous research. Psychophysical and cortical measures were strongly correlated [$r(19)=.65$, $p=.002$]. [a]Weber, 1978/1834; [b]Weinstein, 1968; [c]Penfield and Boldrey, 1937; [d]Penfield and Rasmussen, 1950 (esp. Fig. 17, pg. 44).

2PD threshold (rank)[a,b]	Adjusted Area of S1 Cortex (rank)[b,c,d]
Middle Finger (20)	Lips (20)
Index Finger (19)	Nose (19)
Thumb (18)	Thumb (18)
Ring Finger (17)	Little Finger (17)
Little Finger (16)	Sole (16)
Lips (15)	Ring Finger (15)
Cheek (14)	Middle Finger (14)
Nose (13)	Index Finger (13)
Palm (12)	Big toe (12)
Big toe (11)	Forehead (11)
Forehead (10)	Cheek (10)
Sole (9)	Calf (9)
Abdomen (8)	Upper Arm (8)
Chest (7)	Forearm (7)
Forearm (6)	Thigh (6)
Shoulder (5)	Back (5)
Back (4)	Shoulder (4)
Upper Arm (3)	Palm (3)
Thigh (2)	Chest (2)
Calf (1)	Abdomen (1)

VM instructors teaching BSM assert that even while sitting quietly, *without* overt tactile stimulation, attention can nonetheless be turned to the conceptual, emotional, tactile and visceral experiences related to the present state of the body (Goenka, 2000). During BSM, practitioners focus their awareness progressively on every point of the body's surface, waiting until an experience of some kind arises and calmly registering its occurrence. Certain areas (e.g., fingertips, face) tend to yield very clear, intense experiences, while others (e.g., back, legs) tend to be more dull and undifferentiated (Goenka, 2000).

A working hypothesis of 'neurophenomenology' (Lutz and Thompson, 2003) is that self-reports will correlate better with objective measures in individuals with contemplative training (Lutz et al., 2008). We made a preliminary examination of this hypothesis by leading a cross-sectional group of meditators (1 hr – 15,000 hrs of experience) through a session of BSM (Goenka, 2000) for approximately 30 minutes, and immediately afterward collecting their subjective reports on the sensitivity of 20 regions throughout the body. These subjective scores were then correlated with objective psychophysical and cortical measures of tactile sensitivity gleaned from previous research (described above). Individual correlations between subjective reports and objective measures ('introspective accuracy') were found to be significantly higher for expert vs. novice meditators on all measures used. Introspective accuracy on all measures was also significantly predicted by overall meditation experience, BSM experience, and intensity (mean monthly hours) of meditation practice.

To our knowledge, this represents the first study to investigate a continuous and representative cross-section (novices to experts, with experience spanning 15,000 hrs) of meditation experience, yielding significant differences between experts and novices, as well as results that may be suggestive of training effects.

1.2 Study 2 (Neuroimaging): Brain Gray Matter Density

While plasticity in the adult mammalian brain was once thought to be absolutely minimal, if not impossible (Cajal & May, 1959), structural plasticity at the microstructural (dendritic spine density, axon process length, etc.) scale is now well an accepted fact. Though investigation of adult structural brain hetereogeneities due to learning-induced plasticity generally remains restricted (due to the limitations of current neuroimaging methodologies) to the mesostructural (grey matter volume and concentration, white matter integrity, etc.) level in humans, nonetheless wide evidence is now available for such plasticity in the adult brain.

More impressive still has been the discovery of neurogenesis (growth, differentiation, and proliferation of new neurons) in the adult brain, now well-documented in song birds (Goldman and Nottbohm, 1983), rodents (Altman and Das, 1965) and a variety of other mammalian species (Fuchs & Gould, 2000), including humans (Eriksson et al., 1998).

Such changes in neural structure are typically associated with overt physical practice, training, environmental enrichment, and the like; yet the possibility remains that purely mental practice and exercises, which have been shown to have measurable and positive effects on an enormous variety of skills as measured behaviorally, will have a corresponding effect on brain structure.

Because of the popularity of meditation practices, and the unusual ardor with which its mental practices are undertaken by many adherents, meditative contemplation is a nearly ideal case for studying the possibility of mental practice influencing brain structure. At least two studies using pre-post designs and suitable control groups have now shown grey matter concentration (Holzel et al., 2011) and white matter integrity (Tang et al., 2010) changes in brain structure after relatively brief periods of meditation practice – changes that tentatively can be causally attributed to the mental practices involved.

Futher, a number of earlier between-groups studies comparing highly experienced meditation practitioners with meditation-naïve control subjects have also shown suggestive differences (summarized in Table 1.2). To summarize findings particularly relevant to the present study, neuroimaging has shown that in *vipassana* meditators the insula, a region whose grey matter volume predicts the accuracy of interoceptive reports (Critchley, Wiens, Rotshtein, Öhman & Dolan, 2004), exhibits increased cortical thickness (Lazar, Kerr, Wasserman, Gray, Greve, et al., 2005) and grey matter density (Hölzel, Ott, Gard, Kempel, Weygandt, et al., 2008), as well as increased fMRI blood oxygen-level dependent (BOLD) signal during present-centered awareness (Farb, Segal, Mayberg, Bean, McKeon, et al., 2007). Structural and functional augmentations of primary and secondary somatosensory cortices, including increased cortical thickness (Grant, Courtemanche, Duerden, Duncan & Rainville, 2010; Lazar et al., 2005) and fMRI-BOLD signal (Farb et al., 2007), have also been found in expert meditators from various traditions. Finally, significantly thicker cortex (Lazar et al., 2005) and increased grey matter density (Vestergaard-Poulsen, van Beek, Skewes, Bjarkam, Stubberup, et al.,

2009) in RLPFC/BA10 have also been reported in meditators, suggestive of generalized enhancement of a region strongly implicated in introspection (Fleming et al., 2010; Christoff & Gabrieli, 2000). (A summary of all morphometric studies of meditation to date is given in Table 1.3).

Table 1.3: Summary of all morphometric studies of meditation.

Study	**Meditation tradition**	***N* (meditators / controls)**	**Morphological measure**	**Regions identified (meditators > controls)**
Lazar et al. (2005)	Insight	20/15	Cortical thickness	R anterior insula; R middle and superior frontal sulci
Pagnoni and Cekic (2007)	Zen	13/13	Gray matter volume (VBM in SPM5)	No age-related decline in L putamen
Hölzel et al. (2008)	Insight	20/20	Gray matter density (VBM in SPM2)	L inferior temporal lobe; R insula; R hippocampus
Vestergaard-Poulsen et al. (2009)	Tibetan Buddhist	10/10	Gray matter density and volume (VBM in SPM5)	R orbito-frontal cortex; R thalamus; L inferior temporal lobe; R hippocampus
Luders et al. (2009)	*Various*	22/22	Gray matter volume (VBM in SPM5)	R orbito-frontal cortex; R thalamus; L inferior temporal gyrus; R hippocampus
Grant et al. (2010)	Zen	19/20	Cortical thickness	R dorsal anterior cingulate cortex; secondary somatosensory cortex
Tang et al. (2010)	Integrative body-mind training	22/23	Fractional anisotropy (DTI in FSL 4.1)	L anterior corona radiata; L superior corona radiata; genu of CC; body of CC
Luders et al. (2011)	*Various*	27/27	Fractional anisotropy (DTI)	*Entire brain*
Hölzel et al. (2011)	Mindfulness-Based Stress Reduction	16/17	Grey matter density (VBM in SPM5)	L hippocampus; posterior cingulate cortex; L temporo-parietal junction; cerebellum

DTI: diffusion tensor imaging; VBM: voxel-based morphometry; SPM: Statistical Parametric Mapping (Wellcome Department of Cognitive Neurology, London); L: left; R: right; CC: corpus callosum; MBSR: Mindfulness-Based Stress Reduction.

Though presenting intriguing results, there are two major limitations to consider with respect to morphometric studies of meditation thus far: (i) the use of purely exploratory (as opposed to truly hypothesis-driven) methodology, with an agnostic stance with respect to what is expected to differ in the brains of meditators (and corresponding *post hoc* interpretation of results); (ii) the pooling of highly experienced meditators from a variety of widely disparate, and *prima facie* non-equivalent, traditions of practice. Every morphometric study of meditation to date suffers from at least one of these limitations (some from both). Here we circumvented both problems by recruiting a relatively homogenous group of practitioners who (i) focus intensively on a particular practice (though not entirely to the exclusion of other techniques); (ii) show measurable behavioral advantages over novices in particular skills related to their meditation technique (Fox et al., accepted); (iii) engage in a practice heavily related to awareness of the body, which lends itself to strong, justifiable, and testable *a priori* predictions about potential changes in brain structure that may be due to this practice.

Due to the focus on body-scanning meditation (BSM – see above) in these practitioners, we predicted grey matter concentration increases in regions key to somatosensation (primary and/or secondary somatosensory cortices), interoception (insular cortex), and introspection generally (BA10/RLPFC).

2 METHOD

2.1 Study 1 (Behavioral): Introspective Accuracy

2.1.1 Subjects

A total of 42 meditation practitioners ('meditators') participated. Four participants' data were dropped due to noncompliance with instructions (e.g., circling more than one answer on the sensitivity scale), leaving a total of 38 participants (19 female; mean age = 41.7±16.1 years). All participants had prior experience with and interest in meditation (mean time since beginning meditation practice = 11.0±10.3 yrs), though overall hours of experience (MED) varied enormously (M = 2051±3600 hrs; *min.* = 1.0 hrs; *max*. = 15,000 hrs). The range of experience with the BSM practice, though not as extensive, also varied greatly (M=154±322 hrs; *min.* = 0 hrs; *max.* = 1643 hrs), and was correlated with MED [$r(37) = .36$, $p = .025$]. Participants were recruited through the UBC Meditation Community, the B.C. Insight Meditation Society, and referrals. The University of British Columbia Behavioral Research Ethics Board approved the study protocol. Participants provided informed consent and were debriefed at the end of the experiment.

2.1.2 Procedure

Most participants (n = 30), including all novices, were led through a session of BSM (25–35 min.) by one of three highly experienced meditation teachers. A few (n = 8) highly experienced meditators (300 - 15,000 hrs experience), who had previously received detailed instruction in BSM from a qualified instructor (via intensive retreats of

10+ days) were permitted to practice BSM independently. 33 of 38 participants had at least some experience with BSM. Following the meditation, meditators answered a questionnaire about their subjective experiences during the BSM session (below); finally, participants filled out a brief biographical questionnaire.

2.1.3 Objective Measures of Tactile Sensitivity

Psychophysical Measure Average values for two-point discrimination (2PD) thresholds for each of 20 body regions, as reported in previous research, were used. Data are from 48 participants (mean age = 22 years; 24 female) (Weinstein, 1968). The 2PD task measures the minimal interstimulus distance required to perceive two simultaneously applied stimuli as distinct (Weber, 1978/1834), with the regional sensitivity of the skin varying markedly (Weinstein, 1968) (Table 1).

Cortical Measure Average values for total area in primary somatosensory cortex (S1) for 20 body regions were likewise gleaned from prior published research. Rank-order values for average total area of cortex in S1 dedicated to a given body region were used. Data are based on Penfield and Boldrey (1937) and Penfield and Rasmussen (1950); rank-orderings for cortical area adjusted for skin surface area (ACA; 'adjusted cortical area') follow Weinstein (1968) (Table 1). Cortical data represent aggregated sensation reports from 126 patients undergoing neurosurgery involving direct galvanic stimulation of S1 (Penfield and Boldrey, 1937). Further electrophysiological explorations of S1 have largely confirmed the work of Penfield and colleagues, with minor modifications (Woolsey et al., 1979; Celesia, 1979). Parallel explorations of S1 with magnetoencephalography (MEG; Hari et al., 1993) and fMRI in both humans (Hammeke, Yetkin, Mueller, Morris, Haughton, et al., 1994) and monkeys (Disbrow, Slutsky, Roberts, and Krubitzer, 2000) further support the results of Penfield and colleagues.

Composite Somatic Sensitivity Rank (SSR) As the objective measures (2PD and ACA) were found to be highly correlated (r = .65, p = .002), a composite Somatic Sensitivity Rank (SSR) was calculated by averaging the rankings from both measures for each body region. The SSR represents a mixed psychophysical-cortical measure of somatic sensitivity, and provided a convenient single value of 'somatic' sensitivity for a given body region.

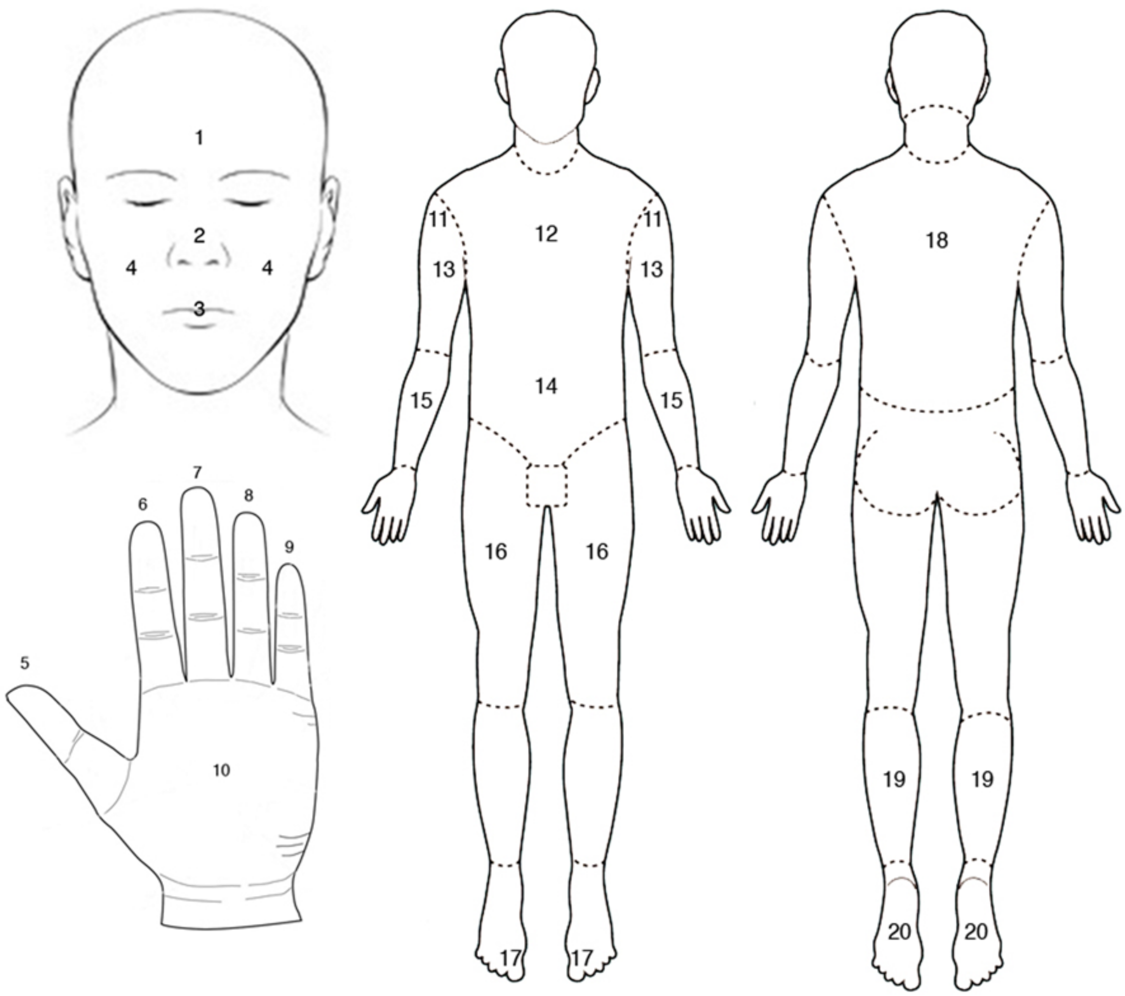
2.1.4 Subjective Measure of Tactile Sensitivity

Sensory Sensitivity Survey Following the session of BSM, participants silently and individually filled out a survey of their subjective experiences during the meditation. Detailed instructions were provided and the experimenter was available to resolve any difficulties. The survey showed diagrams of the body (Fig. 2.2) alongside a simple scale (Fig. 2.1) asking for the "clarity and/or intensity" of sensations in each region *relative* to each other region. Obvious differences in 'body-awareness' were obviated by requiring use of the full range of the scale, such that even highly experienced practitioners rated *some* region(s) '1' (lowest sensitivity *for them*). Similarly, novices rated as '9' the region(s) with the highest sensitivity *for them*. Thus the survey required participants to introspect on and evaluate the relative intensity of their experiences during BSM, examining *relative* differential clarity/intensity of experience for each of the 20 regions, regardless of absolute clarity or intensity.

Figure 2.1: The rating scale used to assess subjective tactile sensitivity for each of the 20 body regions investigated.

1	2	3	4	5	6	7	8	9
Very unclear, weak sensation				Moderate clarity / intensity of sensation				Very clear, intense sensation

Figure 2.2: The body diagrams used for subjective sensitivity rankings.



2.1.5 Measuring Expertise

A major methodological question is how to measure ‘experience’ or ‘expertise’ in the context of meditative training. Here meditators reported overall hours of meditation experience in general, and BSM in particular. When examining a wide range of experience with respect to a particular skill, achievement is typically related to experience level logarithmically (Fredrick and Walberg, 1980). Such nonlinear relationships between achievement and practice time, suggestive of diminishing returns with invested practice, have been demonstrated for an enormous variety of mental and physical skills (Ericsson, Krampe and Tesch-Romer, 1993; Fredrick and Walberg, 1980), including possibly meditation (Jha et al., 2010). We observed a comparable effect here, where hours of experience and introspective accuracy exhibited a logarithmic relationship (see Results).

2.1.6 Data Analysis

Behavioral data were analysed with SPSS 18. Sensitivity scores for each of the 20 body regions were collected from participants and then correlated with psychophysical (2PD), cortical (ACA) and composite (SSR) measures, resulting in three correlation scores for each subject. Higher psychophysical discriminative capacity is represented by smaller interstimulus distances in mm, and higher cortical area rank is likewise represented by smaller values, whereas in the subjective sensitivity scale used (Fig. 2.1), high values represent high sensitivity for a given body area. Thus, for the sake of clarity, all objective measures were reverse rank-ordered (Table 1.2), so that strong positive correlations represent a close fit between subjective and objective measures, or higher 'introspective accuracy' (IA).

2.2 *Study 2 (Neuroimaging): Brain Grey Matter Concentration*

2.2.1 Subjects

We recruited 8 long-term meditation practitioners, partially overlapping with the sample used in Study 1, for the neuroimaging phase (Study 2). Specifically, three meditators in this sample participated previously in the behavioural phase (Study 1). T1-weighted 3D anatomical brain data for 8 control subjects (matched for age and gender) were obtained from the University of California at Los Angeles (UCLA) International Consortium for Brain Mapping (ICBM) database of normal adults (http://www.loni.ucla.edu/ICBM/Databases/).

Subjects were paid $10/hour for time spent outside the scanner, and $20/hour for time spent within the scanner. The UBC Clinical Research Ethics Board (CREB) and the UBC MRI Research Centre approved the study design, and all subjects provided written informed consent.

2.2.2 MRI Data Acquisition

Imaging was conducted at the UBC MRI Research Centre. MRI data were collected using a 3.0-Tesla Philips Intera MRI scanner (Best, Netherlands) with a standard 8-element 6-channel phased array head coil with parallel imaging capability (SENSE; Pruessmann et al., 1999). Head movement was restricted using foam padding around the head.

For each subject, we collected a high-resolution 3DT1 anatomical volume (SPGR: TR = 2 s; TE = 3.53 ms; 175 interleaved axial slices covering the whole brain, 1-mm thick with 0 mm skip; FOV = 25.6 × 25.6 × 17.5 cm; matrix size = 256 × 250; 1 x 1 x 1 mm^3 isotropic voxels).

2.2.3 Data Preprocessing

All preprocessing was performed offline using SPM8 statistical parametric mapping software package (Wellcome Department of Imaging Neuroscience, London). Each subject's high-resolution structural image was co-registered to the mean functional image, and then segmented to produce a grey matter image. We then normalized the segmented images to match a grey matter template . Lastly, an 8-mm full-width at half maximum (FWHM) Gaussian kernel was applied to spatially smooth the data.

2.2.4 Voxel-Based Morphometry Data Analysis

Detailed methods explaining voxel-based morphometry assessments have been published elsewhere (Ashburner and Friston, 2000). Briefly, pre-processed data were globally normalised to correct for overall brain size differences. For the between-groups analysis, no further covariate was added, and the two groups' (meditators and controls) averaged grey matter segmented images were compared using a two-sample *t*-test. For the regression analysis, the logarithm of hours of meditation experience was entered as a covariate of interest alongside the grey matter segmented images for all meditators only.

3 RESULTS

3.1 Study 1 (Behavioral): Introspective Accuracy

3.1.1 Novices Contrasted with Experts

To explicitly contrast novice and expert meditators without setting an arbitrary hours-of-experience threshold for either group, the sample was divided into quartiles by overall hours of meditation experience (MED). This division relied solely on the assumption that those meditators with the most experience would differ from those in our sample with the least experience, and was therefore blind to actual individual correlations with the various objective measures. Within our sample of 38 meditators, this resulted in two groups of nine participants each: MED-Experts (n = 9, mean MED = 7231$\pm$4410 hrs; 6 male; mean age = 50$\pm$18 yrs) and MED-Novices (n = 9, mean MED = 28$\pm$24 hrs; 6 female; mean age = 29$\pm$8 yrs). Individual correlations with each objective measure were Fisher-transformed (Fisher, 1915) and averaged within groups to obtain mean, group correlations for each measure. The two groups' means were compared with independent samples t-tests, which showed significant differences between Experts and Novices across all measures, thus suggesting more accurate introspective reports in Experts as compared to Novices (Table 3.1).

Table 3.1: Average correlations with each objective measure for MED-Expert and MED-Novice meditators.

Objective Measure	**MED-Experts (*n*=9)**	**MED-Novices (*n*=9)**	**Comparison of mean *r*'s**	**Effect size (Cohen's *d*)**
2-Point Discrimination	mean r = .46	mean r = -.01	$t(16)=2.229$, $p=.041$	1.12
Adjusted Cortical Area	mean r = .31	mean r = -.16	$t(16)=2.677$, $p=.017$	1.31
Somatic Sensitivity Rank	mean r = .44	mean r = -.11	$t(16)=2.787$, $p=.013$	1.39

We similarly divided our sample into upper and lower quartiles by BSM experience (again, blind to IA scores), creating BSM-Expert (n = 9, mean BSM = 571±469 hrs; 6 males; mean age = 43±17 yrs) and BSM-Novice (n = 9, mean BSM = 0.40±0.55 hrs; 5 males; mean age = 43±19) groups. Independent samples t-tests comparing the average (Fisher-transformed) correlations were likewise significant for all measures (Table 3.2), and effect sizes were larger than when comparing MED-Experts and MED-Novices.

Table 3.2: Average correlations with each objective measure for BSM-Expert and BSM-Novice meditators.

Objective Measure	**BSM-Experts (*n*=9)**	**BSM-Novices (*n*=9)**	**Comparison of mean *r*'s**	**Effect size (Cohen's *d*)**
2-Point Discrimination	mean r = .64	mean r = .18	$t(16)=3.004$, $p=.008$	1.51
Adjusted Cortical Area	mean r = .41	mean r = .06	$t(16)=3.365$, $p=.004$	1.69
Somatic Sensitivity Rank	mean r = .58	mean r = .12	$t(16)=3.134$, $p=.006$	1.57

Raw subjective scores on the Sensory Sensitivity Study were then averaged for the top (MED-Experts) and bottom (MED-Novices) quartiles of participants. This resulted in average raw subjective sensitivity scores for each body region, for both Experts and Novices. Experts' averaged subjective sensitivity scores were found to correlate highly significantly with SSR (r = .87, p < .001) (Table 3.3). Conversely, Novices' averaged subjective sensitivity scores did not correlate significantly with SSR ($r = -.23$, n.s.) (Table 3.3).

Table 3.3: Correlations between composite objective body sensitivity and Novices' (blue) mean raw scores as well as Experts' (red) mean scores for each body region.

***r* = .87, *p* < .001**

Somatic Sensitivity Rank (2PD+ACA)	Novices' Sensitivity Score (mean; 1-9)	Experts' Sensitivity Score (mean; 1-9)
Thumb (20)	Back (6.3)	Lips (7.4)
Lips (19)	Abdomen (5.9)	Thumb (7.4)
Middle Finger (18)	Chest (5.8)	Index Finger (7.2)
Little Finger (17)	Lips (5.4)	Middle Finger (7.0)
Index Finger (16)	Palm (5.0)	Little Finger (7.0)
Nose (15)	Thumb (5.0)	Palm (6.8)
Ring Finger (14)	Thigh (4.9)	Nose (6.7)
Sole (13)	Forehead (4.9)	Ring Finger (6.3)
Cheek (12)	Shoulder (4.8)	Sole (6.2)
Big toe (11)	Nose (4.8)	Big toe (6.1)
Forehead(10)	Index Finger (4.7)	Forehead (6.0)
Palm (9)	Cheek (4.4)	Abdomen (6.0)
Forearm (8)	Middle Finger (4.1)	Cheek (5.7)
Upper Arm (7)	Little Finger (3.9)	Chest (5.4)
Calf (6)	Ring Finger (3.7)	Shoulder (5.0)
Abdomen (5)	Forearm (3.6)	Back (5.0)
Chest (4)	Sole (3.6)	Forearm (4.8)
Shoulder (3)	Calf (3.4)	Upper Arm(4.7)
Back (2)	Big toe (3.4)	Thigh (4.6)
Thigh (1)	Upper Arm (3.1)	Calf (4.4)

***r* = -.23, n.s.**

3.1.2 Introspective Accuracy and Overall Meditation Experience

Taking the entire sample as a whole (not merely Experts and Novices), overall hours spent in all forms of meditation combined (MED), which included hours spent in BSM, significantly predicted the relationship between subjective sensitivity scores and all objective measures (Table 3.4). As the relationship showed a logarithmic tendency, suggestive of diminishing returns on invested practice, the natural logarithm (*ln*) of total hours of experience was taken (logMED). Relationships with all objective measures were likewise significantly predicted by logMED (Table 3.4; Fig. 3.1A, 3.1B).

Figure 3.1: Introspective accuracy with respect to cortical area (A) and two-point discrimination threshold (B) as predicted by overall hours of meditation experience.

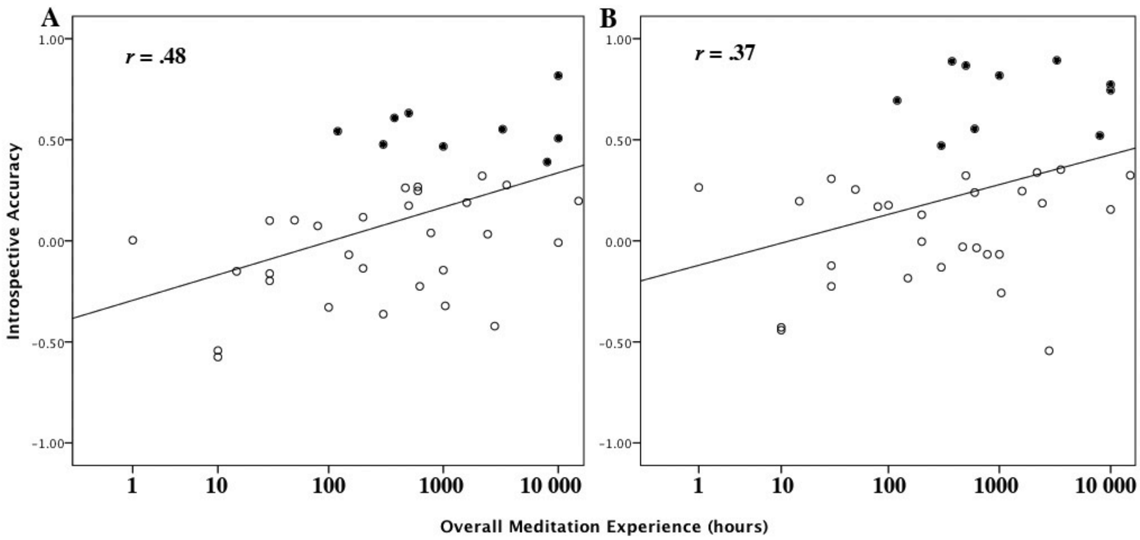


Table 3.4: Correlations between sensitivity as ranked by various physiological measures and as ranked by subjective reports, regressed on overall meditation experience (MED) or BSM experience. Significant correlations here show that individual introspective accuracy improves with increasing meditation experience.

	Introspective Accuracy Correlated with Measure of Meditation Experience			
Objective Measure	**MED**	**logMED**	**BSM**	**logBSM**
2-Point Discrimination	*r*(37)=.33, *p*=.046	*r*(37)=.37, *p*=.024	*r*(37)=.39, *p*=.009, one-tailed	*r*(37)=.34, *p*=.019, one-tailed
Adjusted Cortical Area	*r*(37)=.38, *p*=.020	*r*(37)=.48, *p*=.003	*r*(37)=.32, *p*=.026, one-tailed	*r*(37)=.32, *p*=.026, one-tailed
Somatic Sensitivity Rank	*r*(37)=.39, *p*=.019	*r*(37)=.45, *p*=.006	*r*(37)=.39, *p*=.009, one-tailed	*r*(37)=.36, *p*=.014, one-tailed

3.1.3 Introspective Accuracy and Body-Scanning Meditation Experience

The total number of hours previously spent in body-scanning meditation (BSM) significantly predicted the relationship between first-person sensitivity reports and all objective measures (Table 3.4); the natural logarithm (*ln*) of hours of BSM experience (logBSM) also significantly predicted all relationships (Table 3.4). As we predicted *a* *priori* that meditators with more BSM experience would have improved correlations at the individual level, one-tailed tests were used for these analyses.

3.1.4 Introspective Accuracy and Practice Intensity (PI)

As most participants (36/38) provided a precise date when they first began meditating, we derived a rough measure of 'practice intensity' (PI) by dividing total hours of meditation experience by number of months since beginning meditation practice for each participant. This resulted in an average number of hours spent in meditation per month over each participant's meditation career. Individual correlations with objective measures were regressed on Practice Intensity, which significantly predicted IA for all measures: PI with 2PD, [$r(35) = .36$, $p = .034$]; PI with ACA, [$r(35) = .45$, $p = .007$]; PI with SSR, [$r(35) = .43$, $p = .009$].

3.1.5 Age and Gender

Neither age ($M = 41.1 \pm 16.1$ yrs) nor gender (19 female, 19 male) significantly predicted individual correlations with any of the objective measures used (for age: all r's $< .19$, all p's $> .27$; for gender: all r's $<.10$, all p's $>.58$).

3.2 Study 2: Neuroimaging

3.2.1 Meditation-naïve Controls Contrasted with Experts: Exploratory Analysis

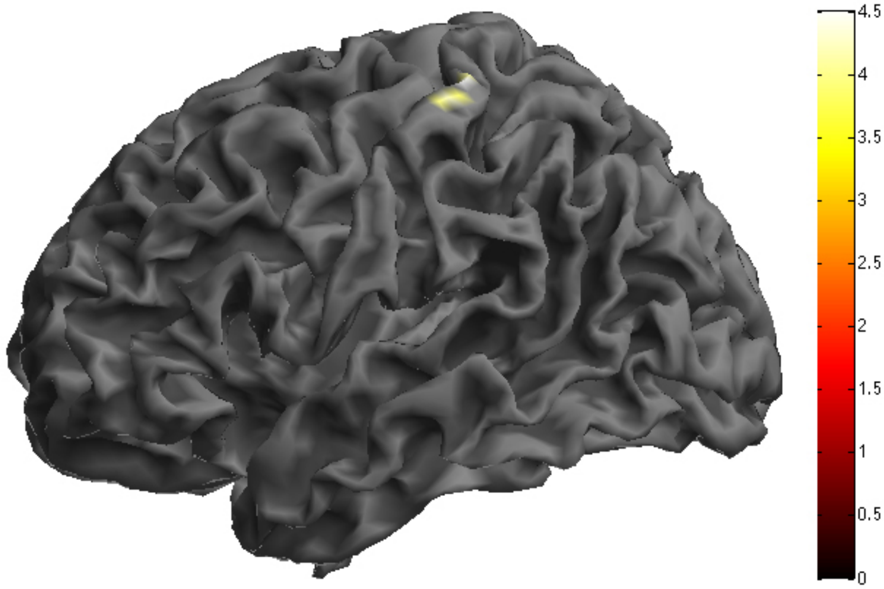
We first compared whole-brain grey matter concentration between meditation-naïve controls and long-term meditation practitioners who specialized in BSM. A rigorous analysis using a Family-wise error rate of .05 revealed no significant differences (either Meditators > Controls, or Controls > Meditators). We thus undertook an exploratory whole-brain analysis (Meditators > Controls) at a statistical threshold of $p < .001$, uncorrected for multiple comparisons. At this more liberal threshold, a between-subjects t-test revealed a single significant cluster of 108 voxels in the left primary somatosensory cortex, $t(14) = 4.55$, $p < .001$ (uncorrected), spanning Brodmann Areas 1 and 3 (Table 3.5, Fig. 3.2).

Table 3.5: Increased grey matter concentration differences in the primary somatosensory cortex of long-term body-scanning meditation practitioners.

			MNI coordinates				
Region	**Hemisphere**	**BA**	**X**	**Y**	**Z**	***t*-score**	**Voxels**
S1	Left	1/3	-43	-31	61	4.55	108

Reported region is significant at $t > 3.79$, $p < .001$ uncorrected. BA = Brodmann area. S1 = primary somatosensory cortex.

Figure 3.2: Enhanced grey matter concentration in left primary somatosensory cortex in meditators vs. controls (BA 1/3).



3.2.2 Grey Matter Concentration Differences Correlating with Body-Scanning Meditation Experience

Next, we correlated grey matter concentration with the log-transformed hours of experience with the body-scanning meditation practice, to investigate whether specific regions showed increasing grey matter density with increasing body-scanning meditation experience. (Behavioral results in Study 1 strongly suggested that log-transformed hours of experience were the best predictor of behavioral differences, hence the use of log-transformed hours of BSM experience in this analysis. Highly similar differences (results not shown) were seen when using raw hours of meditation experience). Our analysis resulted in significant differences in 7 main regions (Table 3.6). Notably, of these 7 regions, 6 are known to be directly and critically involved in somatosensation, interoception, or coordinated skill learning (see Discussion).

Intriguingly, we observed somatosensation-related grey matter concentration differences at many levels of the information-processing hierarchy: early sensory data transmission and relay (dorsal pulvinar of the thalamus; Fig. 3.3), primary cortical centres for processing somatosensation (Penfield & Boldrey, 1937; S1), integrative centers for processing interoceptive information (Critchley et al., 2004; insula; Fig. 3.4), as well as upstream, multimodal regions implicated in the higher-order representation of the sense of physical self in three-dimensional space (Berlucchi & Agliotti, 1997; inferior parietal lobule; Fig. 3.5). While predicted beforehand and amenable to a simple interpretation with the present population of meditators (intensive focus on the body increases grey matter concentration in corresponding regions), prior studies have found similar results in primary somatosensory cortex (Grant et al., 2010) and the insula (Lazar et al., 2005; Hölzel et al., 2008) with meditators specializing in a variety of different practices, not just BSM. This is understandable insofar as essentially all Buddhist meditation practices involve a component (often strong) of focus on present-moment experience, which almost by definition tends to involve awareness of the body's posture, muscle-tone, respiration, etc.

We also observed such differences in a set of regions collectively implicated in skill learning, particularly motor skill learning. The declive and culmen of the cerebellum have been noted to be involved in fine motor coordination (Strick et al., 2009), a finding which may at first appear surprising in the present context (but see Discussion).

We further observed grey matter concentration differences in the left caudate nucleus, long known to be critically involved in simple skill learning, as well as the left superior temporal gyrus.

Table 3.6: Peak voxels for regions exhibiting increasing grey matter concentration with increasing meditation experience in BSM practitioners.

			MNI coordinates				
Region	**Hemisphere**	**BA**	**X**	**Y**	**Z**	**Z-score**	**Voxels**
Pulvinar (Dorsal)	Left	–	-19	-28	11	7.06	183
Insula (Anterior)	Right	13/47	46	13	4	6.66	143
IPL	Right	40	67	-36	29	6.53	731
STG	Left	22	52	-2	0	7.01	339
STG	Left	13	-55	-45	19	6.47	197
Culmen (CB)	Right	–	19	-49	10	6.89	596
Culmen (CB)	Left	–	-12	-42	-9	6.38	235
Declive (CB)	Left	–	-31	-71	-18	6.45	180
Declive (CB)	Right	–	6	-63	-15	6.35	1606
Caudate Nucleus	Left	–	-14	20	11	6.70	111

Reported regions are significant at $t > 52.897$, $p < .01$ FWE corrected with a minimum cluster size of k = 100 voxels. BA = Brodmann area. CB = Cerebellum. IPL = Inferior Parietal Lobule. STG = Superior Temporal Gyrus.

Figure 3.3: Increasing grey matter concentration in the left dorsal pulvinar nucleus of the thalamus with increasing meditation experience.

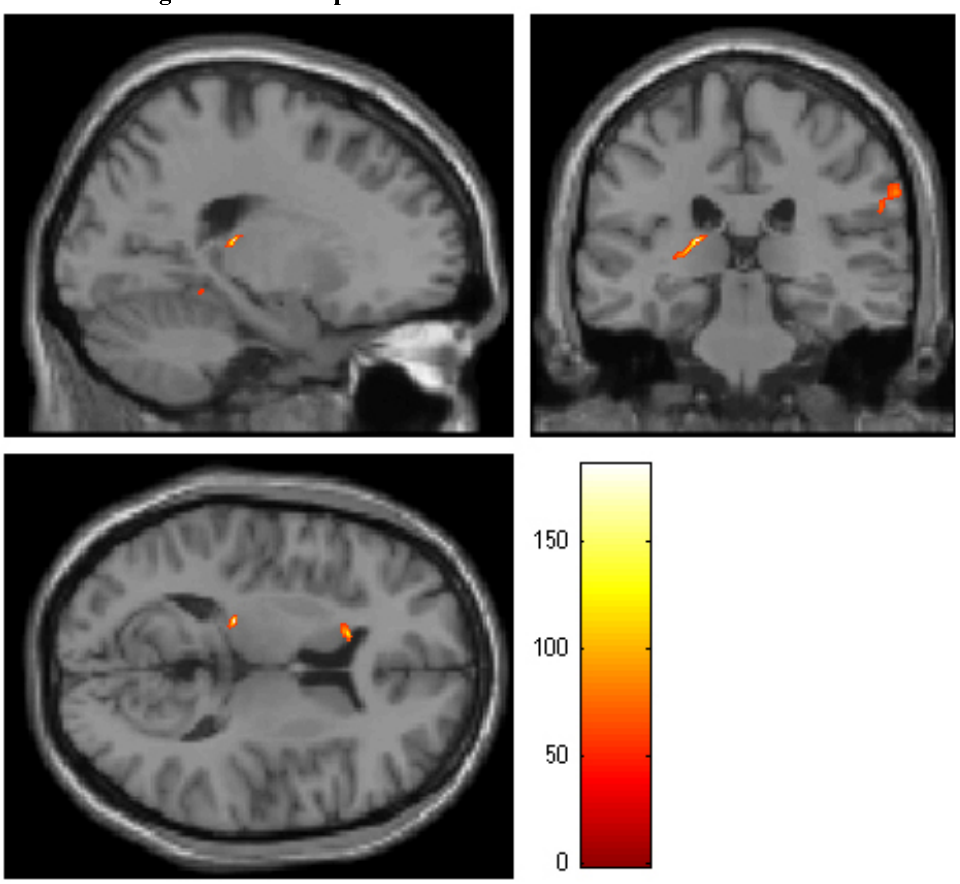
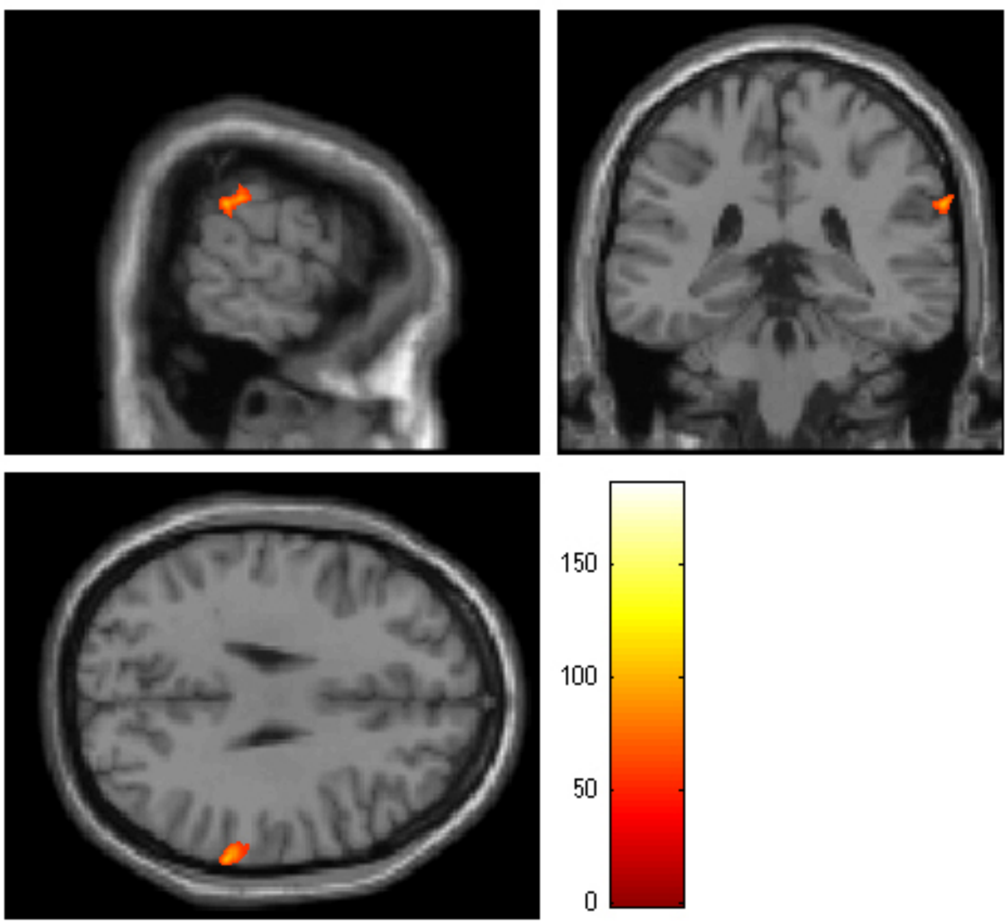


Figure 3.4: Increasing grey matter concentration in right anterior insular cortex with increasing meditation experience.

Figure 3.5: Increasing grey matter concentration in right inferior parietal lobule with increasing meditation experience.



4 DISCUSSION

4.1 Enhanced Introspective Accuracy in Meditators

Not long ago, Nisbett and Wilson (1977) argued that “the accuracy of subjective reports is so poor as to suggest than any introspective access that may exist is not sufficient to produce generally correct or reliable reports” (p. 233). Our results stand in stark contrast to this conclusion. We found that in highly experienced *vipassana* meditators, subjective reports of the clarity and/or intensity of experiences during a body-scan meditation correlated significantly as a group (and often at the individual level) with two objective measures of relative sensitivity gathered from prior published research, as well as with a composite measure combining psychophysical and cortical data. Novice meditators, in contrast, did not show significant correlations at the group or individual level with any measure. Pooling all subjects, we found that overall meditation experience, overall BSM experience, and Practice Intensity all significantly predicted individual introspective accuracy on all measures, suggesting that not only overall experience, but also the ardor of meditation practice may contribute significantly to introspective accuracy.

Though subject to wide variability, the general trend suggests that with increasing meditation experience, reports of subjective tactile experience are more and more closely aligned with what would be expected from a purely neurophysiological perspective. The simplest interpretation of these results is that subjects with greater meditation experience may provide more accurate reports of mental experience.

An alternative explanation is that the perceptual acuity of VM meditators has been heightened in the tactile modality. On this view, long-term meditators would be neither better introspectors on, nor more accurate reporters of, inner experience, but simply more perceptive than novices.

We consider this an unlikely explanation of our results, however, for several reasons: (i) no overt tactile stimulation was actually present in our study. The origin of the sensations subjectively experienced during BSM may be peripheral (arising from activity at the skin's mechanoreceptors, or peripheral nerves), central (arising from activity in somatosensory regions of the brain), or some combination of both. In any case, whatever meditators are reporting on, it does not involve perceptual discrimination of explicit sensory stimulation; (ii) reports were retrospective: even if all experiences arose peripherally (e.g., at the mechanoreceptors of the skin), meditators were reporting on second-order representations of these experiences held in memory, rather than making real-time perceptual judgments; (iii) reports were evaluative: meditators were specifically instructed to evaluate their overall experience during the BSM session and give *relative* ratings of intensity for each region, rather than simply reporting the intensity for a given body region. The subjective reports, therefore, do not constitute reports of sensory experience, but rather judgments of the clarity of various (recalled) internal experiences relative to one another; (iv) it is tempting to assume that sensations subjectively 'felt' throughout the body at the level of the skin would bear a closer relation to peripheral than central nervous system activity (and hence best considered perceptual or sensory, rather than strictly 'mental,' experiences). The first study to test this hypothesis in humans, however, found no evidence for a direct relationship between intensity of sensation as measured by subjective reports versus by density of action potentials in the median and ulnar nerves (Knibestöl and Vallbo, 1980). The authors concluded that cortical areas were thus far more likely to play the central role in generating subjective tactile experience, *even during overt tactile stimulation* (Knibestöl and Vallbo, 1980). During BSM, where no overt tactile stimulation is present, this seems all the more likely – inconsistent with the notion that enhanced accuracy of reports is due solely to improvements in low-level sensory acuity.

So while a heightening of perceptual acuity may also indeed result from long practice of BSM, and may support or interact with introspection on experiences during meditation, we believe that the enhancement of introspective accuracy remains the most parsimonious explanation of our results.

4.2 Increasing Grey Matter Concentration with Meditation Experience

We examined the whole brain in order to explore whether any regions showed increasing grey matter concentration as meditation experience increased. We found numerous such regions (Table 3.6), most of which can be divided into either body awareness-related or skill learning-related brain regions.

We found increasing grey matter concentration in the dorsal pulvinar of the thalamus, the anterior insula, and the inferior parietal lobule. The dorsal pulvinar is part of the thalamus, whose main function is that of a sensory relay station through which incoming sensory input passes before arriving at cortical centres. The dorsal pulvinar in particular is typically where exteroceptive tactile sensory information (touch, pain, heat, etc.) is relayed to primary cortical somatosensory regions. The anterior insula, as already discussed, is strongly implicated (complementarily) in *interoception*, the processing and awareness of internal bodily states (heartbeat, respiration, digestion, etc.) (Critchley et al., 2004); whereas the inferior parietal lobule subserves a higher order representation of the body and self in physical space (Berlucchi and Aglioti, 1997). The changes in these regions, scaling with amount of meditation experience in a body-awareness-related technique of meditation, strongly suggest that the mental practice itself is inducing the changes and thus may be causally responsible for the differences observed.

Another set of regions can be linked to skill learning generally: the culmen and declive of the cerebellum and the caudate nucleus. Besides their key role in motor coordination, however, these regions have now been linked to a wide variety of cognitive skills, including attention, working memory, and visualization (Strick et al., 2009).

A possible explanation for this is that nature of the body-scanning meditation itself. The practice involves far more than simple awareness of the body: rather, attention is focused systematically on increasingly smaller regions, with increasingly fine resolution, as the practice progresses, and strong emphasis is laid on developing a particular sequence which is followed (no pun intended) 'religiously' (Goenka, 2000). What the practice amounts to is a coordinated series of mental (imagined) 'movements' of attentional focus, following a very specific sequence with high spatial precision. We consider it highly likely that such mental exercises would recruit the cerebellum, though our present results cannot speak to the question.

4.3 Putative Neural Basis of Enhanced Introspective Accuracy

The potential mechanisms of enhanced introspective accuracy remain an intriguing question. Inter-subject differences in introspective accuracy are predicted by grey matter volume in RLPFC/BA10 (Fleming et al., 2010), and within subjects, the practice of introspection itself modulates activity in this same region (McCaig et al., 2011). If intensive introspective practice during meditation recruits RLPFC/BA10, use-dependent structural or functional alterations there might explain the enhancement of introspective accuracy – and as noted above, two studies have already reported structural differences in this region in long-term meditators (Lazar et al., 2005; Vestergaard-Poulsen et al., 2009). Considering the specific nature of the meditation engaged in by BSM practitioners, we consider plasticity in cortical regions related to body awareness (e.g., S1, insula) another important means whereby introspective accuracy for tactile sensitivity might be improved. Use-dependent plasticity is well known in somatosensory brain regions (Elbert et al., 1995; Pantev et al., 2001), and the grey matter volume of the insula has been shown to predict the accuracy of interoceptive reports (Critchley et al., 2004). As noted earlier, alteration of structure and/or function has been demonstrated in both these regions in long-term meditators (Lazar et al., 2005; Hölzel et al., 2008; Farb et al., 2007; Grant et al., 2010), and such changes may mediate enhanced body awareness.

How might body awareness and introspection interact? As BSM involves the intensive, simultaneous practice of both awareness of the body, as well as introspection on thoughts and emotions, a kind of Hebbian learning may take place: the concentrated, frequent coupling of dispassionate introspection with attention to the body may enhance introspective accuracy for internal experiences related to the body especially, as well as for mental events generally. That is, even as more (or more detailed) information about the state of the body is reaching awareness, the objectivity with which experience is considered increases, resulting in an enhanced, more objective awareness of the body and the mental experiences related to its momentary experience. Conversely, practitioners who engage in non-BSM forms of meditation may enhance introspection specifically, which generalizes to an enhanced awareness of the body. Supporting this possibility, a recent study found that individual introspective accuracy is stable across multiple different perceptual tasks, and may thus rely on a relatively general system (Song et al., 2011); if so, *enhancements* of introspective accuracy, too, may ameliorate a single multi-purpose system, leading to generalizable improvements – a view consistent with the claims advanced by meditation practitioners that "the development of awareness with any particular meditation technique will automatically result in a marked increase in one's general level of awareness, thereby enhancing one's capacity to be mindful in regard to situations that do not form part of one's primary object of meditation" (Analayo, 2003; p.22). Pending further study, however, views on the potential mechanisms whereby introspective accuracy might be enhanced and/or generalizable to other domains remain speculative. Clearly, much research remains to be done in this nascent area.

Mental training resulting in cortical plasticity therefore represents to us the most plausible mechanism whereby finer tactile discrimination, and correspondingly improved first-person reports, are generated – in the same way that physical training results in reorganization of cortical somatosensory areas in Braille readers (Hamilton and Pascual-Leone, 1998) or mental training using rt-fMRI neurofeedback has resulted in increased activation in somatomotor cortex during imagined hand movements (DeCharms, Christoff, Glover, Pauly, Whitfield, & Gabrieli, 2004). We hasten to add, however, that our results (though suggestive) cannot prove a causal origin of meditation experience for either the enhanced introspective accuracy or grey matter concentrations observed. A possible, though to us implausible, explanation remains that these differences are pre-existing in meditation populations, and happen to predict the amount of time a given practitioner will dedicate to their meditation practice.

4.4 Meditation as Mental Training

We agree with others (Slagter et al., 2011) in conceptualizing meditation as a form of 'mental training,' and as such, subject to the diminishing returns observed nearly ubiquitously among many forms of mental and physical training (Ericsson et al., 1993; Fredrick and Walberg, 1980), including potentially meditation (Jha et al., 2010). We thus argue for meditation as a form of mental skill learning, subject to the same benefits and constraints as many other forms of skill learning studied in psychology: gradual improvement with practice (no matter what the level of experience), subject, however, to diminishing returns (Ericsson et al., 1993).

Indeed, the foundational Buddhist text on meditation training, the *Satipatthana Sutta*, explicitly compares meditative training to fine motor skill learning: "The discourse compares this progress to a skilled turner who attends to his lathe with full awareness… The simile of the turner suggests increasing degrees of refinement and subtlety in practicing mindfulness… just as a turner makes progressively finer and more delicate cuts on the lathe" (Analayo, 2003, p. 130).

Unlike many skills, however, we found evidence that the introspective skills of experienced meditators may be generalizable: unexpectedly, overall meditation experience was a better predictor of introspective accuracy than total BSM experience. While unanticipated, these results are consistent with research showing generalizable improvements in perceptual discrimination and sustained attention (MacLean, Ferrer, Aichele, Bridwell, Zanesco, et al., 2010) as well as visuospatial processing (Kozhevnikov, Louchakova, Josipovic, & Motes, 2010) in experienced meditators. The generalizability of contemplative skills is also consistent with the claims made by scholars and instructors of meditation, who claim that "…the development of awareness with any particular meditation technique will automatically result in a marked increase in one's general level of awareness, thereby enhancing one's capacity to be mindful in regard to situations that do not form part of one's primary object of meditation" (Analayo, 2003, p. 22).

Interestingly, though not all expert meditators demonstrated high introspective accuracy, *no* novice meditators did: the least-experienced meditator to achieve significant scores at the individual level had 120 hrs of meditation experience, and on average those who achieved individually significant introspective accuracy had in excess of 1000 hrs of experience, further suggesting that extensive experience is indeed an important factor. Further exploration of potential meditation training effects using experimental (rather than cross-sectional) designs thus seems warranted.

Closer inspection of our data also showed that the participants whose introspective accuracy was high but who had very little BSM experience always had significant experience (in the thousands of hours) with other forms of meditation (data not shown). This result further supports the view that meditative skills are generalizable; it also suggests that the predictive power of BSM experience is actually quite strong, but is underestimated here because meditators with extensive experience in other practices can perform well on the body-awareness task of introspective accuracy, despite having little explicit BSM training.

4.5 The Purpose and Possible Benefits of Body Awareness Meditation

The value of paying close attention to sensations may not be apparent at first. The negative effects of detachment from the objective state of the body, however, are considered important elements in a variety of disorders, from depression to anorexia (Cash & Deagle, 1997). Modern authorities on meditation consider BSM an essential practice, suggesting that "contemplation of feelings [i.e., sensations] is a meditation practice of considerable potential. This potential is based on the simple but ingenious method of directing awareness to the very first stages of the arising of likes and dislikes, by clearly noting whether the present moment's experience is felt as 'pleasant,' or 'unpleasant,' or neither. Thus to contemplate [sensations] means… to know how one feels, and this with such immediacy that the light of awareness is present before the onset of reactions, projections, or justifications in regard to how one feels. Undertaken in this way, contemplation of [sensations] will reveal the surprising degree to which one's attitude and reactions are based on this initial affective input provided by [sensations]" (Analayo, 2003, p. 157).

Ernst Weber, the father of the psychophysical measures used in the present study, similarly concluded that the valence of sensations at a very early stage formed a key link in the causal chain leading to emotions, noting that sensations often result in automatic, emotional reactions to stimuli, with correspondingly diminished self-reflection and cognitive control. He wrote:

> One effect of the intensity of many feelings provided by common sensibility is that the mind is prevented from calmly contemplating them in the manner necessary for the sensation to be referable to objects. Instead, the attention of the mind is driven by the pains to its own state of suffering, and its own body. The effect of this is that the sensations excite not so much the cognitive faculties as the faculty of desire, so that we are driven to avoid the pain by instinctive or intentional movements… [When] pain is evoked, the faculty of desire is excited in the mind, and calm reflection is prevented. (Weber, 1978, p. 153-4).

In this vein, a recent study with subjects undergoing an 8-week Mindfulness Based Stress Reduction (MBSR) course found increased fMRI-BOLD signal in lateral prefrontal regions concurrent with heightened activity in the insular and secondary somatosensory (SII) cortices during present-centered awareness (Farb et al., 2007). These activations were interpreted as suggestive of a more objective, detached assessment of one's mental and physical state, as opposed to rumination on the emotional or self-referential meaning of a given experience; our results support this interpretation, inasmuch as experienced meditators in our study tended to furnish more objective first-person reports of sensation. We agree with others, however, in underscoring the important distinction between mere attention to somatic input and truly *accurate* perception of this information (Critchley et al., 2004), since excessive attention to sensations themselves is in fact implicated in a host of mental and physical disorders (e.g., Cash and Deagle, 1997). The calm, objective assessment of the state of the body may be a key factor, then, in the many benefits engendered by meditation practice, both psychological (Ivanovski & Mahli, 2007) and physical (Creswell, Myers, Cole & Irwin, 2009; Carlson, Speca, Patel, & Faris, 2007).

4.6 Limitations

Numerous limitations must be taken into consideration – most notably the use of averaged psychophysical and cortical measures gleaned from the literature in Study 1. Though we used data from large samples that have been replicated repeatedly (see section 2.1.3), there is no substitute for individual psychophysical testing or cortical mapping. Thus a key question that cannot be answered by the present study concerns the relationship between subjective reports and the individual's objective measures of tactile sensitivity. Future work could examine this relationship by performing psychophysical testing on individual participants, or by using neuroimaging to compare subjective reports with the morphology of key interoceptive (insula) and exteroceptive (somatosensory) areas of the brain already known to be enhanced in expert meditators (Lazar et al., 2005; Hölzel et al., 2008; Grant et al., 2010). Our original aim was to conduct such a regression analysis in Study 2, but too few meditators who completed the neuroimaging phase also completed the behavioural body-scan questionnaire.

Further, though our behavioral results are strongly suggestive of training effects, the cross-sectional nature of our sample of meditators precludes a direct inference regarding the causal link between meditation practice and greater introspective accuracy. Further work could experimentally examine possible training effects from BSM using a pre-post design along with a suitable (e.g., wait-list) control group.

4.7 Conclusions

In summary, we found that introspection, as measured by subjective assessments of tactile experiences during meditation, becomes more accurate with increasing meditation experience, and in a separate group of meditators that grey matter concentration changes consistent with such behavioural changes are evident in multiple regions of the brain.

If this improved introspective accuracy can be generalized to other domains, then experienced meditators may prove to be powerful collaborators for cognitive neuroscientists exploring the neural correlates of higher cognition, abstract thought, and consciousness. Our findings are consistent with studies of experienced meditators showing enhancement of structure and/or function in areas key to interoception (insula), exteroception (somatosensory cortices), and introspection generally (RLPFC/BA10). Further research investigating introspective accuracy in meditators seems warranted, specifically with the aims of determining whether meditation training plays a causal role in the differences observed between novices and experts, and of further elucidating the individual neural or physiological basis for such differences.

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