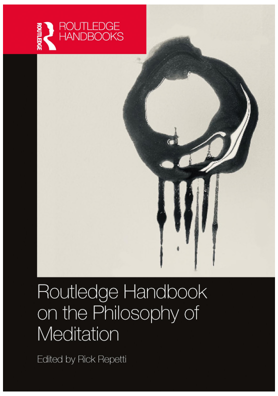

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How meditation changes the brain

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HOW MEDITATION CHANGES THE BRAIN

A neurophilosophical and pragmatic account

David R. Vago

1 Introduction

As His Holiness, the Dalai Lama put it, in his Foreword to *Destructive Emotions*, the text reporting the results of that year's conference exchange between the Dalai Lama, his monastic entourage, and a cohort of Western philosophers, psychologists, and other cognitive scientists,

> Buddhism and science are not conflicting perspectives on the world, but rather differing approaches to the same end: seeking the truth. In Buddhist training, it is essential to investigate reality, and science offers its own ways to go about this investigation. While the purposes of science may differ from those of Buddhism, both ways of searching for truth expand our knowledge and understanding.
>
> *(Goleman 2004, p. xiii)*

Science and Buddhism have a long cross-cultural history of dialogue and debate over how they may be commensurable for human health and well-being (Wallace 2003, Lopez 2008, deCharms 1998, Harrington 2008). In 2005, the most influential voice in the discourse between Buddhism and science, the 14th Dalai Lama, spoke to over 14,000 neuroscientists at the Society for Neuroscience annual meeting. In response to the question, "What if neuroscience comes up with information that directly contradicts Buddhist philosophy?", His Holiness responded, "Then we would have to change the philosophy to match the science". As the Dalai Lama alludes to repeatedly through his interactions with modern scientists and academic scholars, both cognitive science and Buddhism attempt *to reveal the nature of mind and explore its capacity to transcend its own fundamental flaws*. His Holiness alludes to the argument of Buddhist exceptionalism – the idea that Buddhism and Buddhist principles associated with the mind and liberation from suffering may be uniquely suited for scientific investigation. Whether or not there is universal agreement that Buddhist conceptions of mind are naturalistic or more appropriate for scientific investigation than other religious traditions, there is a clear argument for further dialogue between the two traditions. Continuing to explore Buddhist philosophical and experiential descriptions of meditation practice using a cognitive science lens, in the broadest sense of that term,[1] is likely to further a cross-cultural investigation of the mind, of the

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socio-cultural constructions of mind and body, and of the relations of each of these to health, well-being, and human flourishing.

As a systematic form of mental training, the traditional Buddhist spiritual path prescribes an extensive range of meditations, prayers, and behaviors. Yet, contemporary teachings most commonly emphasize mindfulness meditation training, including focused attention (FA), open monitoring (OM), and open awareness (OA), as the most relevant styles of practice (Matko and Sedlmeier 2019, Ospina et al. 2007, Lutz et al. 2007, Kabat-Zinn 2011). More extensive teachings for spiritual progress (e.g., Abhidharma),[2] including ethical, devotional, and philosophical practice, are often reserved for practitioners invested in long-term goals with an emphasis on soteriological outcomes. In this context, meditation is thought to provide a tool for developing insight into the fundamental nature of mind – including a familiarity with one's own mental habits and dispositions, a technological capacity to transcend mental and physical ailments, and a greater understanding of mind in relation to the true nature of reality. Such training includes esoteric descriptions of awakening or enlightenment involving cessation of ego-driven emotional reactivity, cravings, and desires, phasic and increasingly tonic forms of nondualistic phenomenology, dissolution of spatial and temporal boundaries, and characteristics of altruistic motivations and *eudaimonia*[3] (Buddhaghosa 1991, Bodhi 1999). With these larger goals in mind, formal meditation practice is only one part of extensive training developed to leverage insight into the nature of mind, including its relevance to self-development, enaction in the world, and relation to others.

As one reflects on the neuroscience of meditation, one must also acknowledge the motivations and characteristics of the practitioners being studied. Theoretical models of meditation and mindfulness suggest that motivations and aspirational goals for practice can critically influence the outcomes of practice and should be considered independent of any particular set of meditation techniques (Vago and Silbersweig 2012, Gethin 2011, Lutz et al. 2015). The typical long-term meditator who identifies as a modern Buddhist, sometimes referred to as a 'Buddhist sympathizer', is described as an intermediate- or novice-level practitioner whose contact with Abhidharma is mostly through books by English-speaking teachers, who has very little engagement with the Buddhist canon of scripture, and who has a regular meditation practice for under 30 minutes/day that they consider the essence of Buddhism (McMahan 2008).

It is believed that between 200 and 500 million people meditate globally and are some hybrid between traditional and modernist practitioners; their number is increasing. In one report, the number tripled in the US from 2012 to 2017, rising by 14.2% or 35 million (Black et al. 2018). Varied self-serving and altruistic motives account for starting and sustaining a meditation practice (Pepping et al. 2016). Generally, as meditation experience increases from novice to adept, motivation shifts from immediate self-help/self-regulatory goals to continued self-exploration and finally self-liberation and more altruistic motives, a trajectory described from a study of mindfulness-based stress reduction (MBSR) participants and in psychotherapeutic contexts (Carmody et al. 2009, Shapiro 1992). The scientific evidence supporting meditation may also motivate practice (Schmidt and Walach 2014) and provide confidence in the teachings, affording plausible expectations about the training.

The other commonly studied practitioner has experienced a mindfulness-based intervention (MBI) or program (MBP) based on the MBSR protocol (Kabat-Zinn 1982, 2011). The prescriptive standardized protocol for these first-generation MBIs and MBPs involves 18–26 hours of in-person training (1.5–2.5 hour classes) and one 6-hour retreat over the course of 8 weeks (Crane et al. 2017). These courses involve formal training in four core meditation practices, FA, OM, body scan, and movement-based somatic practices (e.g., light yoga, walking meditation), as well as informal practice bringing mindful awareness into everyday life (e.g., brushing teeth, social interactions). Over the past two decades, modified versions of the MBI have emerged to account for various accommodations to patient populations who have time or effort limitations. Mindfulness training is delivered in various formats (e.g., in-person or virtual group, retreat, one-on-one, mobile app), frequencies, durations, and intensities.

Over the last two decades, there have been numerous preliminary investigations of MBIs in single-arm trials to examine efficacy, safety, and health outcomes. These single-arm trials demonstrate that such trainings can 'move the needle' for health outcomes, e.g., stress, anxiety, depression, and pain (Kabat-Zinn et al. 1985, Shapiro et al. 1998, Carlson et al. 2001). Preliminary findings provided the medical community the evidence needed to pursue more rigorous randomized controlled trials (RCTs) that use multiple arms and examine MBIs' therapeutic effectiveness against 'gold-standard' or active control techniques that match the group-based format, teacher–student alliance, therapeutic expectations, and other non-specific effects not directly related to meditation training.

The neuroscience of meditation is also contextualized by the teachers of the practice. A new generation of meditation teachers is being trained with a curriculum that explicitly includes reports of neuroscientific studies on mindfulness, with the intention of informing and motivating individuals to practice (Santorelli et al. 2017). Learning the theory and research that support mindfulness approaches is essential to teacher training and proper adherence to the MBI protocol (Crane et al. 2010). However, many of these teachers are not taught the proper contextualization of research findings, and over-generalization of preliminary findings often leads to distorted claims about the therapeutic benefits. There is evidence for a confirmatory bias associated with the influence of brain images on therapeutic effectiveness (Busch 2019). Some research suggests that having some knowledge of neuroscience alone can influence one's experience of happiness through meditation (Flanagan 2009). Unfortunately, much of the reported neuroscientific data has not yet been replicated and could potentially be deceiving.

Systematic reviews and meta-analyses of randomized controlled trials of MBIs have shown inconsistent results on a variety of standard cognitive (e.g., attention, executive functioning, working memory) and clinical outcome (pain, anxiety, depression, blood pressure, peripheral inflammation markers, and sleep efficiency) measures (Hoge et al. 2021, Ospina et al. 2007, Rubia 2009, Chiesa and Serretti 2010, Hofmann et al. 2010, Gu et al. 2015, Whitfield et al. 2021). The relation between meditation practices and self-reported measures of mindfulness is also inconsistent, and suggests trait-like dispositions or innate capacities are not appropriately being accounted for in cross-sectional analyses. In comparison to active control interventions that attempt to control for non-specific factors, many of the reported benefits of MBIs are equivocal, with only a moderate percentage (~20%) of reports where MBIs outperform the control (Ospina et al. 2007, Rubia 2009, Chiesa and Serretti 2010, Hofmann et al. 2010, Gu et al. 2015, Hoge et al. 2021, Whitfield et al. 2021). Indeed, most studies use a mix of subject populations with varying degrees of clinical or cognitive deficit to begin with, and floor or ceiling effects are often unaccounted for (Davidson and Kaszniak 2015, Van Dam et al. 2018). Yet, the use of meditation practices in the context of integrative health and wellness continues to increase.

Recent neuroscientific studies of meditation indicate correlations between meditation practice and the volume and function of relevant brain structures. Here, I focus on the findings from neuroimaging research of meditation, how the data may be interpreted for health, wellness, and flourishing, and how an integrative perspective may provide the appropriate forum for an interdisciplinary contemplative neuroscience. The implications of such findings in relation to some of the more popular, hyperbolic interpretations, as well as a brief epistemological account of the mind, self-related processing, and the causal relations amongst the body-mind-brain complex are discussed.

2 Neurodharma: From hype to the roots of mind-body medicine

'Neurodharma' has been described as "the truth of our minds – [our joys and sorrows, our suffering and happiness] – grounded in the truth of our own bodies" (Hanson 2020, pp. 7–8). In essence, 'neurodharma' is a neologism emerging from the field of contemplative neuroscience that takes advantage of the popular interest in neuroscience in conjunction with the nomological claims (or 'laws') of the Abhidharma. In *Neurodharma*, Hanson claims to provide seven practices of highest happiness as well as a "new science and ancient wisdom for being as wise and strong, and happy and loving, as any person can ever be". The good sentiment aside, neuroscience has not provided sufficient data to support any of these claims sufficiently well. *Neurodharma* suggests that the "seven practices of awakening" – steadying the mind, warming the heart, resting in fullness, being wholeness, receiving nowness, opening into allness, and finding timelessness – will increase happiness, wisdom, and strength (*id.*, p. 5). One may believe these promises, and there may be preliminary research support for some aspects of these abstract claims, but such definitive statements are misleading and invite unfair criticism of neuroscientific methods within contemplative neuroscience.

Dharma practitioners, Buddhist sympathizers, and novice practitioners all practice some similar styles of meditation, but significant differences in motivation/intention, goals, context, and intensity/frequency of practice are also notable. As a Dharma practitioner, one must prescribe to fundamental beliefs in the "four seals", "noble truths", or propositions that lead to liberation and awakening, including impermanence and the no-self doctrine. Some Buddhist philosophers have argued that using a neuroscientific lens to better understand these aspects of salvation, liberation, or awakening is flawed (Thompson 2020). In this context, Thompson supposes that such claims are not naturalistic and therefore not appropriate, or accessible, to the scientific method (*id.*). Following this argument, neuroscience could never prove the existence of no-self. Notably, Hanson says his claims are "sacred", "ultimately beyond science and logic", which allows him to wax "metaphorical and poetic" (2020, p. 5). Thompson uses the example of studying brain states during the experience of listening while Yo Yo Ma plays Bach's cello suites to further dismiss the neurodharma or the "neural Buddhism" idea that tracking such complex phenomenology to particular neural substrates is even possible: "although that information would presumably be useful for understanding the effects of musical training and expert performance on the brain, it would tell us very little about music, let alone Bach" (2020, p. 163).

Perhaps the soteriological aspects of self-transcendence, spiritual experience, and nonduality are beyond the scientific method and the scope of measurement, similar to the qualia associated with a beautiful sunset or the experience of love. Perhaps, however, these are the religious roots of mind-body medicine, not only providing inspiration for investigating the healing potential of mental effort and its influence over bodily systems, but a legitimate narrative by which distinct moral and social concerns about modernity may be amplified (Harrington 2008). If humanity is to evolve a mental capacity to move beyond destructive emotions and embrace many of the discoveries in positive psychology that shed light on placebo, nocebo, positive reappraisal, and well-being, meditation will remain at the center of our approach to physical medicine, neuroscience, and psychotherapy (Duckworth et al. 2004, Colloca and Barsky 2020, Garland et al. 2011).

One argument in alignment with the integrative, more moderate view is Thompson's claim that cognition is more accurately reflected in an embodied perspective that is embedded in a contextually relevant world (2020). An integrative neurophenomenological view would embrace the embodied, enactive, embedded, extended perspective (Newen et al. 2018), yet would not dismiss brain imaging as an appropriate modality with which to study any experience of a human mind. Any phenomenon that involves a sensory impression can be studied using a neuroscientific lens, keeping in perspective that neuroscience is limited by the strength of its measurement and technology; e.g., neuroscience does not yet have the tools to measure imperceptible, yet impactful consequences of electrical or magnetic energy emitted by our bodies on the world around us, nor can it yet resolve the impact of much of the electromagnetic spectrum of energy in the world around us on the individual, but fMRI or other methods could potentially capture correlates of function or morphology associated with those phenomena.

Thompson (2020) describes the 'cosmopolitan' perspective as one which may adjudicate the complex relationship between religion and science through exploring the presuppositions and commitments across different religious, scientific, philosophical, and artistic traditions. Fruitful dialogue could use a 'cosmopolitan' approach so that neither Buddhism nor science is using one to embellish or justify the other. Rather than integrate Buddhist ideas directly into the cognitive science framework, differences in philosophy can be discussed and respected individually – in contrast to Buddhist modernism. A translational or integrative approach takes a more moderate view and claims there is a valid logic to integrate neuroscientific methods along with phenomenological and behavioral analyses to study some of the more nonconceptual and non-ordinary phenomena reported in the context of spiritual practice.

The soteriological aspects of many practices may be elusive, but if there are reportable phenomena that individuals experience and the phenomena are replicable across different individuals, then the scientific method can appropriately characterize them using phenomenological tools as well as objective methods. Will the experience of nonduality by contemporary/modernist practitioners mimic what was experienced in 1400 CE in the monastic setting? Probably not, but there are likely to be meaningful similarities that can be appropriately re-contextualized for consumption in contemporary settings. At the least, an Abhidharma view on impermanence and no-self can offer inspiration through a nonconceptual lens and be insightful from a conceptual point of view. For example, as a mindfulness practitioner, one learns through skillful teachings that all phenomena are temporary as are the physical constituents that make up the human body.

An example of a study relevant for teaching the concepts of impermanence and no-self involves a study at the University of Bologna that determined that the physical bodies of adult humans are made of about 40 trillion cells (Bianconi et al. 2013). There is no static self in any cell or collection of cells. We lose approximately one brain cell every second – and they are not replaced. This is one example of concepts from Abhidharma re-contextualized with a real-world example from the scientific literature. Incorporating Buddhist concepts into the cognitive and neuroscience discourse benefits the science of meditation and science of mind. Some of the historical neurophysiological findings below demonstrate how research on meditation has contributed to our understanding of body-mind-brain interactions.

2.1 The neurophysiology of meditation: Electrophysiology (EEG)

The use of electroencephalography (EEG) to study the brain began in 1929, yet the first neuroscientific study of advanced meditators using EEG methods was in 1961 (Anand et al. 1961). They report on four yogis sustaining a state of *samādhi* (Sanskrit: deep concentration) while keeping their hands immersed in ice cold water for 45–55 minutes. They found persistent, increased amplitude alpha band (8–12 Hz) activity both before and during this practice. All four yogis demonstrated an ability to prevent alpha-blocking by various sensory distractions, including loud noises, strong lights, and other sensory stimuli. Alpha-blocking reflects distraction by external stimuli, and the yogis demonstrated a capacity to inhibit distraction. Another study was conducted shortly thereafter on Soto Zen adepts with varying levels of expertise (1–20+ years' experience) (Kasamatsu and Hirai 1966). Interestingly, the Zen adepts did not exhibit increases in beta (18–20 Hz) and gamma (>40 Hz) waves like the yogis who practiced *samādhi* (Das and Gastaut 1955).

Many studies were conducted on Transcendental Meditation (TM), a proprietary mantra technique introduced by Maharishi Mahesh Yogi. Herbert Benson and colleagues famously investigated the physiology of how TM induces a "relaxation response" in somatic variables, including reducing blood pressure in hypertensive subjects (Benson et al. 1974). The first scientific report on TM practitioners controlling their cardiac and respiratory physiology was published in *Science* (Wallace 1970). Since 1970, the science of meditation has slowly increased the volume and rigor with which it has investigated the impact of meditation on body-mind-brain interactions, and has attracted popular media and interest from the rich and famous, making meditation a trendy wellness activity (Atkinson 1975). The popularization of TM, the conflicts of interest around funding sources, confirmation biases, and reports of poor methodological quality created many skeptics for some of the claims (Tøllefsen 2013, Bai et al. 2015). A similar caution has been issued around the influence of the Dalai Lama on studies of Tibetan styles of practice and the more modern mindfulness research movement, in which scientific researchers are antecedently committed to belief in the benefits of meditation and, perhaps consequently, their research reports too often fail to publish null results (Van Dam et al. 2018, Thompson 2020).

The majority of EEG time-frequency analyses that have followed up until the present day have similar reports to the original studies from the 1960s and 1970s (Lee et al. 2018). Across styles of meditation, increased slow alpha (8–9 Hz), power/amplitude (40–70 μv), and occasional theta (5–7 Hz) trains in midline frontal areas (anterior cingulate, medial frontal gyrus), with a decrease in the intensity of delta (2–4 Hz) and beta (12–14 Hz) waves, are most often reported (Cahn and Polich 2006, Kaur and Singh 2015, Schoenberg and Vago 2019, Aftanas and Golocheikine 2001, Travis and Shear 2010). One demonstrated that alpha band functional network topology is better integrated in experienced meditators than in novice meditators during meditation (van Lutterveld et al. 2017). This entire physical pattern is one of relaxed, but alert, wakefulness. Frontal midline theta has also been shown to arise during states of creativity, flow, and focused concentration (Katahira et al. 2018, Kubota et al. 2001). One seminal study demonstrated very clear gamma band (25–42 Hz) activity during non-referential compassion meditation that correlated with subjective reports of phenomenal clarity (Lutz et al. 2004). Gamma band activity during meditation has been replicated elsewhere, and it reflects the global coherence of brain activity and perceptual binding of information (Braboszcz et al. 2017).

While these results reflect progress identifying specific electrophysiological markers of meditation, some fundamental questions remain. Cardiovascular, hormonal, and metabolic changes, behavioral effects, and alterations of neurophysiology and phenomenology resulting from meditation have been explored in recent years. Most meditative states have been shown to have a particular physiological profile suggestive of an alert, but hypometabolic, state with decreased sympathetic nervous system activity, and increased parasympathetic activity through influence on vagal tone (Jevning et al. 1992): i.e., although meditation requires arousal and attention, it facilitates a somatic relaxation response, lowers heart rate, helps regulate breathing, and boosts melatonin. There is some evidence that – given the hypometabolic state – meditation likely provides some of the restorative functions of sleep and thus decreases the biological pressure and need for sleep. For example, in long-term meditators, one study found that hours spent in meditation are associated with a significant decrease in total sleep time when compared with age- and sex-matched healthy individuals who did not meditate (Britton et al. 2014).

The existing time-frequency analyses of meditation are limited in scope to the most common FA and OM meditation styles. Focusing on one dimension of the EEG signal and only a few styles of practice to draw interpretations/conclusions regarding meditation training is problematic since it does not theoretically align with a complex, integrated understanding of the brain, the rich typology of practices, and associated brain-mind mechanisms uniquely supporting advancement of the practitioner (Schoenberg and Vago 2019). Recent proposals suggest that investigating EEG-correlates of meditation with non-linear methods encompassing induced (non-phase-locked) signal processing techniques may disentangle emergent properties of meditation supporting the idea that the brain represents a highly complex non-linear dynamical system (Schoenberg and Speckens 2014, Schoenberg and Vago 2019). This growth in sophistication of method is gradually improving our scientific understanding of meditation in ways that complement the insights contained in the extant contemplative neuroscience literature.

For example, multivariate auto-regressive modelling, topological mathematics with implications for holographic representations (Burch and Di Falco 2018) of brain functioning, and hyperspace string theory have all been furthering exploration of the brain-mind system from outside the established paradigms (Shaw and Routray, 2018, Schoenberg and Vago 2019). A recent review of the literature and prescriptive agenda for future meditation research suggests novel methods to: (a) concisely classify discrete and developmentally specific states of consciousness in line with the subtle, complex phenomenology of meditative experience, (b) identify new measures, classification, and quantification systems with non-linear dynamics, and (c) map developmentally specified mind states and stages to neurobiological substrates based on discrete EEG band functionality, phenomenological significance, and underlying neurophysiological mechanisms.

2.2 The neurophysiology of meditation: Functional magnetic resonance imaging (fMRI)

Current neuroimaging research utilizes analyses based on measurement of regional cerebral blood flow (CBF) or glucose metabolism; morphological or volumetric abnormalities using voxel-based morphometry (VBM), measures of cortical thickness, gray matter density, gyrification, white matter connectivity, or diffusion weighted imaging (e.g., diffusion tensor imaging); and multivariate statistical models to quantify unique patterns of functional activity and causally linked connectivity between regions. Modern correlational and topographical fMRI methods are based on the functional parcellation of the brain into 180 anatomical regions and about 10 unique resting state networks (RSNs) (e.g., default mode network, central executive network, etc.) that generally cluster together by spatially and temporally coherent spontaneous low-frequency (<0.1 Hz) CBF fluctuations (Loukas et al. 2011, Sporns 2013, Vago and Zeidan 2016, Yeo et al. 2011). Due to the high cost of neuroimaging, studies almost always involve small sample sizes (typically, $n < 20$). Smaller sample sizes actually have the benefit of rendering it *less* likely that sample size alone will drive 'significant' effects (Friston et al. 1999). Yet, strict significance thresholds for the *t*-tests upon which the effect sizes are based, combined with low statistical power, will nonetheless produce inflations of the reported effects compared to the true effect size, biasing 'significant' results (Schmidt 1992, Yarkoni 2009, Hupé 2015, Fox et al. 2016).

Despite these limitations, considerable variation in study design and methodology, and the heterogeneity of study populations, significant progress has been made in the last 20 years in delineating circuitry underlying states and traits of meditation. Here, I review findings from the last two decades and provide evidence for emerging neurocircuitry models of meditation focusing on critical circuits of cognition and emotion, particularly brain networks regulating the evaluative, expressive, and experiential aspects of self-awareness, self-regulation, self-transcendence, and self-integration (Chiesa and Serretti 2010, Vago and Silbersweig 2012, Holzel et al. 2011, Raffone et al. 2019, Brandmeyer et al. 2019).

Systematic reviews and meta-analyses of brain imaging studies targeting meditation states and traits report unique characteristics across functional regions and networks of the brain (Fox et al. 2014, 2016, Tang et al. 2015, Falcone and Jerram 2018, Sezer et al. in press). State activation changes reflect functional activity during a particular practice, while trait changes implicate stable transformation from baseline patterns of passive non-meditative rest, or cross-sectional differences in long-term practitioners reflecting accumulative changes or unique lifestyle dispositions. Critically, one must consider that study designs and meditation practice experience have varied vastly across studies, ranging from 4 to 40 years of experience on average in one review (Fox et al. 2016).

2.2.1 Structural brain changes in meditation

Changes in brain morphology (volume and shape) are thought to reflect differences in brain structure related to a particular medical condition, normative development, age-related decline, or plastic changes due to a learned experience (Thomas and Baker 2013). Changes in cortical thickness and subcortical volume have been reliably tracked as part of normal age-related atrophy, and annual reductions of up to 1.0% in most brain areas of adults over 20 years old have been found (Fjell and Walhovd 2010). The volumetric brain reductions in healthy aging are unlikely to be related to neuronal loss. Rather, synaptic pruning, reductions of synaptic spines, and decreased myelination of axons probably account for the reductions in gray matter (neuron cell bodies). Normal age-related atrophy is likely to account for reductions in specific cognitive abilities, e.g., processing speed, executive functions, and episodic memory, and can explain group differences between younger and older adults.

A number of considerations of morphological changes warrant caution in interpretation. First, the cranium has a finite capacity, and growth in gray matter or even cortical thickness is limited. Measured differences are confounded by individual variability in gender, genetic factors, personality traits, or diseases of the vasculature. Increases in size do not necessarily reflect improved function. Limitations in experimental design, statistical methods, and methodological artifacts often drive reported effects, further undermining the evidence for deriving meaning from reports of training-dependent structural changes (Thomas and Baker 2013). Nevertheless, interesting findings have driven a narrative that meditation may be neuroprotective for age-related atrophy in areas associated with executive functioning, sensory processing, interoception, and meta-awareness.

One of the first morphological studies of meditators analyzed the cortical thickness of 20 long-term mindfulness practitioners with 9.1 ± 7.1 years' experience who practiced 6.2 ± 4.0 hours per week (Lazar et al. 2005). They found the right anterior insula and right middle and superior frontal sulci (Brodmann Area 9; BA9/10) to be significantly thicker in meditators than in controls. Interestingly, there was an age-related interaction, such that apparent atrophy in the anterior insula and frontal polar cortex (FPC; BA 9/10) observed in 40- and 50-year old control subjects was not apparent in meditation practitioners, suggesting meditation may be neuroprotective of age-related cortical thinning, as 40- and 50-year old meditators compared to 20- to 30-year old meditators and controls showed the same average thickness (Lazar et al. 2005). Interestingly, a correlation was also found between cortical thickness in the left inferior occipito-temporal visual cortex, change in respiration rate, and the amount of meditation practice, suggesting advanced practitioners reduce respiration rate during practice and such changes may be directly related to increased thickness of a particular brain region responsible for visual imagery.

Since 2005, one meta-analysis examined over 20 morphological studies of meditation practitioners from across traditions. Eight brain regions were found to be consistently altered in meditators, including areas key to meta-awareness (frontopolar cortex, BA 10), exteroceptive and interoceptive body awareness (sensory cortices and insula), memory consolidation and reconsolidation (hippocampus), attention regulation (anterior cingulate), and emotional evaluation (orbitofrontal/ventromedial frontal cortex) (Fox et al. 2014). Luders (2015) examined the link between age and cerebral gray matter in a large sample (n = 100) of long-term meditators and control subjects aged between 24 and 77. A negative correlation was found within both groups, suggesting atrophy over time. However, the slopes of the regression lines were steeper for controls than meditators, again suggesting meditation may be neuroprotective for age-related atrophy (Luders et al. 2014). Larger volume and increased gyrification in the right anterior insula have been found to specifically correlate with duration of meditation training (Holzel et al. 2008, Luders et al. 2012). Luders (2011) also demonstrated larger fractional anisotropy (FA) in fiber tracts such as the inferior and superior longitudinal fasciculus and uncinate fasciculus, fiber tracts that connect the ventromedial prefrontal cortex with the limbic structures of the brain, including the parahippocampus, amygdala, and anterior temporal lobe, all of which suggest stronger emotion regulatory pathways in meditators.

2.2.2 Functional brain changes in meditation

The first functional brain imaging study of meditators using fMRI examined five Kundalini (Sikh) Yoga meditation practitioners scanned while passively observing their breathing and silently repeated the mantra, '*sat nam*' ("I am truth") during inhalations and '*wahe guru*' ("wondrous guru") during exhalations (Lazar et al. 2000). This study found activation across regions involved in attention (prefrontal, pregenual anterior cingulate, and parietal cortex), arousal and autonomic control (hypothalamus, midbrain, amygdala), sensory-motor (pre- and post-central gyrus), and skill-based learning (putamen) (*id.*).

Since 2000, there have been over 25 fMRI studies of state and trait effects of meditation, including studies of expert and naïve practitioners of Yoga Nidra (yogic deep relaxation), Kundalini Yoga, Tibetan, Pure Land (Mahayana Buddhist), Acem (secular Norwegian), Vipassana (mindfulness), Zen, Theravaden (traditional mindfulness), Soham (Vedanta), TM (mantra), and visualization forms of meditation, amongst others (Fox et al. 2016, Falcone and Jerram 2018). One meta-analysis of functional studies focused on functional activation changes related to states underlying FA, OM, mantra, loving-kindness, and visualization practices. Predominantly, FA meditation techniques were related to increased activation of the left supplementary motor area (SMA; Brodmann Area (BA 6) and dorsal anterior cingulate cortex (dACC; BA 24), and conversely, deactivation of the medial posterior cingulate cortex (PCC; BA 30) and left inferior parietal lobule (IPL; BA 39). The PCC and IPL are regions associated with the default mode network (DMN), a network responsible for self-related processing, memory retrieval, and passive mind-wandering (Fox et al. 2016). OM practices were related to increased activation in the SMA (BA 6), dACC/SMA (BA 32/6), left mid/anterior insular cortex (BA 13), left inferior frontal gyrus (IFG; BA 44/45), and left SMA (BA 6). FA meditation has specifically been linked to deactivation in the PCC in multiple other studies (Falcone and Jerram 2018, Fox et al. 2016), whereas OM meditation is associated with deactivation in subcortical regions such as the pulvinar and the thalamus (Fox et al. 2016), suggesting unique substrates for FA versus OM practices.

Additionally, more experience with meditation was linked to increased activation in medial frontal regions like the frontal pole (BA10), whereas novice practitioners exhibited increased activation in the insula (Falcone and Jerram 2018). Overall, distinct neural patterns supporting unique forms of meditation remain elusive. A large number of articles are typically excluded ($n = 53$) (Fox et al. 2016) from meta-analyses because of heterogeneity in data acquisition. One notable study focuses on brain activation in adept meditators during the experience of emotional auditory stimuli while practicing a non-referential compassion meditation and found increased activation in the amygdala, right temporo-parietal junction (TPJ), and right posterior superior temporal sulcus in response to all sounds, suggesting greater detection of the emotional sounds, and enhanced mentation in response to emotional human vocalizations for experts than novices during meditation (Lutz et al. 2008). Interestingly, the increased activation of the amygdala could also be interpreted as dysfunctional emotional reactivity, but along with all other observations, it has been interpreted as salient emotional responsivity and equanimity – along with a faster emotional recovery time than novices.

Another study of pain in advanced practitioners (equivalent to 4 years of practice, 19 hours/day) similarly saw greater activation in the sensory and insular cortex during the experience of pain and a faster return to baseline than novices, suggesting little stress reactivity during anticipation, greater emotional expression, and improved emotional recovery (Lutz et al. 2013). These data indicate that the mental expertise to cultivate positive emotion with the expression of compassion alters the activation of circuitries previously linked to empathy and theory of mind in response to emotional stimuli. Furthermore, this and other studies of pain in novice and advanced practitioners suggest meditation experience does not attenuate sensory aspects of nociceptive input, but rather functions to mitigate affective or evaluative dimensions of pain experience through the modulation of descending inhibitory pathways (Zeidan and Vago 2016, Grant et al. 2011, Gard et al. 2012).

2.2.3 Resting state connectivity changes in meditation

Mindfulness training has specifically been found to involve unique connectivity patterns across four specific RSNs: the DMN, central executive network (CEN), frontoparietal (FPN), and salience (SN) networks (Vago and Silbersweig 2012, Sezer et al. in press, Brandmeyer et al. 2019). Descriptions of these networks can be found elsewhere (Sporns 2013, Vago and Zeidan 2016, Yeo et al. 2011). In short, the CEN is associated with executive functioning, the SN is associated with salience detection and interoception, the DMN is described above as supporting self-related processing, and the FPN is a hub-network associated with a circuit-breaking function and flexible switching between networks (Sporns 2013, Vago and Zeidan 2016). Specifically, mindfulness-mediated functional connectivity changes are reported to include: (a) increased connectivity between the PCC, a major node in the DMN, and the dorsolateral prefrontal cortex (dlPFC), a major node in the CEN, which may relate to attention control; (b) decreased connectivity between the cuneus and SN, which may relate to self-awareness; (c) increased connectivity between the rostral anterior cingulate cortex (rACC) region and the dorsomedial prefrontal cortex, a major node in the DMN and FPN, and decreased connectivity between the rACC and amygdala, both of which may relate to emotion regulation through a meta-awareness strategy; and (d) increased connectivity between the dACC and anterior insula, two overlapping nodes in the SN and FPN, which may relate to improved interoception, pain relief, and sensory processing without evaluation.

2.3 Summary of brain imaging: Towards an integrated model of self-transformation

The current neuroimaging data are converging along a particular narrative supported by the emerging theoretical models of meditation (Lutz et al. 2015, Raffone et al. 2019, Schoenberg and Vago 2019, Vago and Silbersweig 2012). The self-awareness, self-regulation, and self-transcendence (S-ART) model delineates particular mechanisms for the development of self-awareness, self-regulation, self-transcendence, and self-integration that support general increases in the size and function of major nodes in the FPN, CEN, SN, and DMN. As parcellation methods and temporal windows for analyses become more advanced, and individualized differences are more adequately addressed, improved neural signatures for meditation will emerge. In general, the data suggest most meditation traditions can improve the strength and stability of activity in the FPN and its flexible coupling and integration with other RSNs depending on the contextual demands to support sustained, unbiased attention, meta-awareness, flexible engagement of attention (between the external world and internal mental space), and controlled reactions of the autonomic nervous system (Brown et al. 2007, Holzel et al. 2011, Vago and Silbersweig 2012, Malinowski 2013, Raffone et al. 2019).

Using graph theoretical analyses, Cole et al. (2013) and others have found that the FPN's brain-wide functional connectivity pattern is among the highest relative to the other networks and this connectivity is flexibly updated according to task demands. These data appear to position this network and the FPC, specifically in a critical integrative and 'circuit-breaking' function critical to self-awareness and self-integration (*id.*, Dixon et al. 2018, Spreng et al. 2013, Burgess et al. 2007). This mechanism of rapid, flexible coupling between FPN and other networks is proposed to be a critical function for self-awareness in advanced practitioners, especially given the strong support for this substrate to be active across styles of practice, preserved from age-related atrophy, and critical for monitoring, prospective memory, and meta-awareness (Vago and Zeidan 2016). Meta-awareness is a key mechanism proposed through the lens of self-transformation that contributes to our fundamental insight into our own mental habits and dispositions. Overlapping constructs for meta-awareness include decentering, disidentification, cognitive defusion, reperceiving, observing self, observer perspective, meta-cognitive awareness, meta-awareness, cognitive distancing, self-distancing, and deautomatization (Bernstein et al. 2015, Deikman 1982, Masuda et al. 2004).

Thinking about the content of one's thought reflects meta-cognition, while meta-awareness reflects awareness of one's focus of attention. Meta-awareness is likely to also integrate interoceptive and exteroceptive input. The improved resolution, clarity, and integration with which one experiences external sensory and internal visceral stimuli are thought to contribute to a more embodied experience, including core biological, ecological, and interoceptive factors. These factors allow a distinction to be made between what is itself and what is not itself, processes extremely basic to all kinds of animal behavior, and which are critically not entangled in the contents of awareness (Varela et al. 1991). The extant literature supports an emphasis on *experiential self processes*, sometimes referred to as 'the minimal self' (Gallagher and Zahavi 2020), including the first-person perspective of pre-reflective, conscious experience, such as kinesthetic or proprioceptive experience, and agency for one's actions (Rochat and Zahavi 2011). This is in contrast to a narrative self-reflective mode of processing supported by the DMN that may contribute to our psychopathologies of depression and anxiety when overactive or interfering with ongoing task demands.

Self-regulation involves processes that are cognitive in nature and contribute to the efficiency and control of thought and behavior. Sustained attention/vigilance is self-regulatory and reflects the ability to sustain attentional focus, remain alert to stimuli over time, and restrict access to information irrelevant to one's goal state. Self-regulation also refers to inhibitory control processes – a fundamental capacity of cognition that restricts access to thoughts, emotions, or behaviors when they are inappropriate or irrelevant to one's goal state (Dillon and Pizzagalli 2007, Aron 2007). Self-transcendent processes support the dissolution of the duality of self/other and support a more integrated/unified experience (Yaden et al. 2017). The interpersonal/integrated self which develops into a social self-consciousness – a self-for-others (Neisser 1997) – helps cultivate prosocial, altruistically motivated behavior, nondual awareness, and joy.

In the face of an ever-changing environment, the continuity and stability of experience are something we can count on and something our mind, brain, and body have learned to perform efficiently. The continuous and willful switching between an internal plan, the demands of the external world, and our judgments and decisions behind each behavior is an impressive feat of coordination across multiple sensory, cognitive, and motor systems, including the cascade of hundreds of thousands of neurochemical reactions at the molecular level. These data support the multiple Asian contemplative traditions that have emphasized systematic forms of training the mind and body to better integrate intentional and automatic processes.

3 Measuring self-transformation: Supporting the emerging field of contemplative neuroscience

Although there have been a significant number of scientific discoveries about the brain from meditation research, our understanding of body-mind-brain interactions is limited by the modern scientific tools of measurement. The findings of scientific studies on meditation are accumulating, creating a body of empirical evidence to benefit future generations. Unfortunately, these findings are based primarily on the newcomers to meditation and limited techniques, and as a whole do not represent the breadth of experience outlined in conventional contemplative teachings. Systematic reviews and meta-analyses of existing RCTs for cognition, emotion, and self-related outcomes have revealed MBIs most generally impact our health and well-being similarly to gold-standard and other active control treatment approaches (e.g., group-based psycho-education, relaxation, nutrition, reading, or social support) (Hoge et al. 2021, Goyal et al. 2014, Whitfield et al. 2021). These clinical trials involve many different sections of the general population who are healthy, report chronic stress, or have some clinical psychiatric symptoms. Essentially, the data indicate that there is little value added to including formal sitting meditation as part of a group intervention for shifting traditional outcomes, including emotion-related outcomes, such as perceived stress, or cognitive skills like attention.

The next generation of contemplative neuroscientific studies will rely heavily on clarifying some of the pertinent issues that have been identified as limitations and rely on emerging technologies and digital data analytics that can capture the complex neural dynamics and associated physiological and embodied phenomena that underlie self-transformation. The development of neurotechnology, artificial intelligence, and big data analytics found in collaborative science will leverage these roots of mind-body science and drive innovation (Pal et al. 2021). Such research may involve volitional first-person phenomenology ranging from the rather common, uncultivated, spontaneous experiences of absorption in an activity, sometimes referred to as 'flow', to philosophical inquiry into the nature of mind, and the most profound, deliberately cultivated experiences of nonduality through meditation. Contemplative research will thrive through an integration of embodied, embedded, and/or enactive forms of cognition, incorporating modern data curation tools, and focusing on cross-disciplinary dialogue. In this approach, the field of contemplative neuroscience may help to better predict clinical outcomes and potential targets for the development of biologically based diagnostic and therapeutic strategies for those suffering with mental illness, advance the healing of physical disorders influenced by mental phenomena, and clarify our understanding of the nature of mind and conscious phenomenology, so that it may benefit humanity.

4 Conclusion

I have offered a comprehensive review of the cognitive science research, broadly construed, on meditation. This analysis reveals that there are significant, philosophically interesting empirical correlations between various types of meditation practice and a variety of measures of cognitive and related functioning. However, the analysis to date undermines many of the hyperbolic claims afloat in popular culture about meditation. Any philosophy of meditation that would be empirically informed must take these findings into account. At the same time, however, a number of these findings are promising, enough at least to validate the idea that further empirical studies and philosophical analyses are warranted, and to ground one of the central hypotheses uniting the chapters in this book, namely, that a philosophical (and empirical) examination of meditation is a worthwhile philosophical endeavor.

Notes

1 Cognitive science "in the broadest sense" is meant to include not only more standard, narrow conceptions that might restrict its domain to cognitive neuroscience, but also to include psychology, philosophy, psycholinguistics, general artificial intelligence, and any other area of scientific inquiry that pertains to cognition, intentionality, mental states, etc.

2 "Abhidharma" literally means "higher Dharma", and "the Dharma" refers to the Buddhist path or teachings, simplifying greatly. The Abhidharma is the set of texts containing the philosophical teachings based on analyses of the other early Buddhist scriptures, which include the recorded sayings of the Buddha and the monastic code.

3 "*Eudaimonia*" is a Greek term loosely but inadequately translated as "happiness", but informally understood in the broader sense of human well-being and flourishing.

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